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THE UNIVERSITY OF ALBERTA

The Progress of the Edgerton Landslides, 1974-1991

by

Kim, Hak Joon

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A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE

DEPARTMENT OF GEOLOGY

EDMONTON, ALBERTA
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Dr. D.M. Cruden

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Dr. T.F. Moslow

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Prof. A. Peterson

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Dr. S. Thomson

Date: 25 July 1992

Abstract

The Edgerton landslides were reactivated in 1974 on the west side of the post-glacial valley of the Battle River, 48km northeast of Wainwright, Alberta. The North Slide has a scarp at an angle of 55°-60° to the horizontal, nearly 14m high and 180m long, and a graben 53m wide. Immediately south of the North Slide, the scarp of the South Slide formed; the scarp has since grown to 8m high and to 250m long. In 1980, the East Slide developed about 0.75km southeast of the South Slide; its scarp has since increased to 18m high and to 260m long. The slope movements occur in flat-lying, poorly indurated, interbedded clay shales, siltstones, and sandstones of Late Cretaceous age.

Airphoto interpretation and field evidence suggest that movement of the landslides proceeded from their scarps to their toes. Borehole samples show fractures, slickensides, and brecciation even though the boreholes penetrated the top of the valley wall unaffected by slope movements. Possible causes of these features are glacier ice-thrusting, valley rebound, and differential swelling of bentonitic clay shale. In addition, surface water flowed directly into the North Slide scarp. The disturbed structures and surface water which flowed into the slope may have reduced the strength of the bedrock significantly. The slope movements were triggered by the increase in pore pressures induced in the slope following the abnormal spring runoff in 1974. Brush clearing behind the North Slide scarp may have contributed to the increase of pore pressures in the scarp area.Post-slide stability analyses suggest that residual strength parameters are being mobilized along the entire rupture surfaces.

Airphoto interpretation and ground surveying suggest that the toes of the North and the East Slides are advancing. The formation of extension cracks within the South Slide suggests it may advance in the future. The bulging of the landslides' feet caused extension cracks in the slide masses which increased infiltration of surface water. Since the bedrock in the area is bentonitic clay shale, the infiltration of surface water might cause swelling of the clay shale, decreasing its strength. Furthermore, pore pressures might build up along the pre-sheared rupture surfaces, causing advancing slope movements.

Acknowledgements

The author would like to thank my supervisor, Dr. D. M. Cruden. His consistent guidance and help were essential for the completion of the thesis.

Thanks are due to Mr. G. Koroluk and Mr. J. Chesterman, on whose properties the landslides occurred, for their permission to enter their land to study these slope movements.

I am grateful to Mr. L. Kolody and other staff at the Alberta Environment, Development and Operations Division, for providing the boreholes and testing.

Dr. S. Thomson and Prof. A. Peterson of the Department of Civil Engineering provided results of ground surveying which were important for the thesis. Dr. S. Thomson also read earlier drafts of the stability analysis and checked the calculations.

I am grateful to Dr. T. F. Moslow of the Department of Geology for discussions on various subjects.

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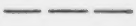
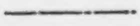
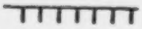
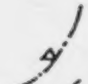
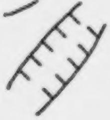
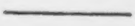
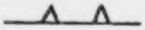
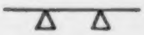
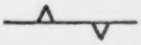
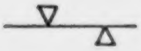
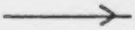
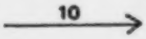
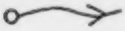
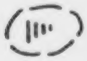
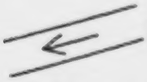
	Sunken feature
	Raised feature
	Scarp, length of downslope lines to give an indication of length of slope, line marks top of feature (Dashed where approximate)
	Toe
	Graben
	Crack
	Breaks of slope (Convex), teeth point downslope
	Breaks of slope (Concave), teeth point downslope
	Breaks of slope (Convex), teeth point downslope
	Breaks of slope (Concave), teeth point downslope
	Drainage channel with direction of flow (Dashed where approximate)
	Surface slope in degrees, measured between head and tail of arrow
	Spring
	Pond
	River with direction of flow
	Horizontal Surface

Chapter 1

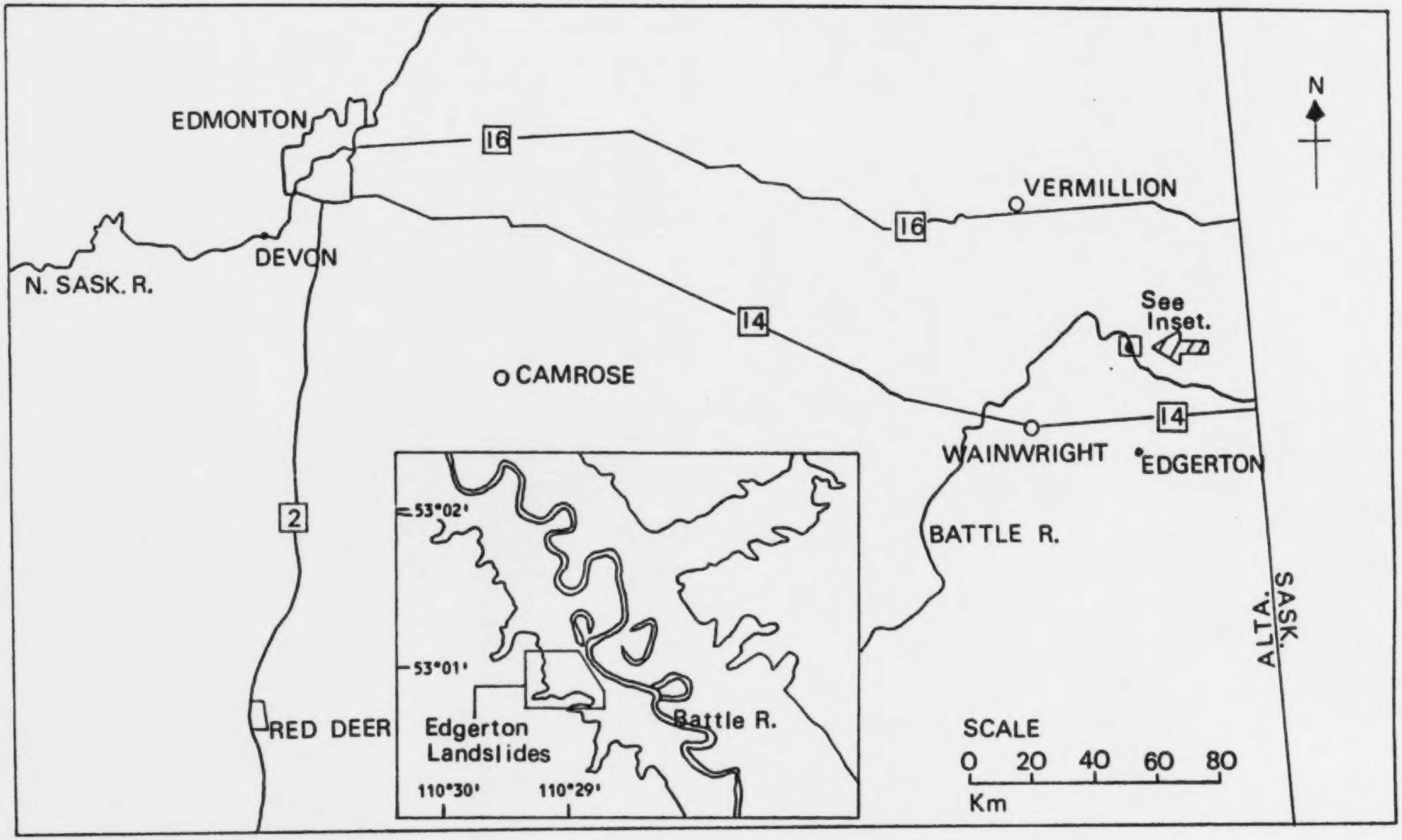
Introduction

1.1 Background

In May, 1974, a crack was observed by Mr. G. Koroluk that traversed his wheat field located about 48km northeast of Wainwright, Alberta (Fig. 1.1). The field is on the west side of the Battle River at the top of a gently sloping valley wall. The valley walls of the Battle River are characterized by extensive relict landslides. Over the summer the crack widened and a scarp developed. A scarp about 2m high had formed before a major movement occurred in late August. Within 1 or 2 days, the slide rapidly extended and when the major movement ceased, a scarp at an angle of 55°-60° to the horizontal, nearly 14m high and 180m long, and a graben 53m wide had evolved. This slope movement was subsequently termed the North Slide by Tweedie (1976).

Immediately south of the North Slide a scarp about 0.5m high and about 160m long had formed at the time of major movement of the North Slide. This slide was subsequently termed the South Slide by Tweedie (1976). This scarp has since increased to about 8m high and to about 250m long in July, 1990.

In June, 1981, an additional slide had developed along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2
BATTLE R.
ALTA.
SASK.
53°02'
53°01'
RED DEER
Edgerton
Landslides
Battle R.
110°30'
110°29'
SCALE
0
20
40
60
80
Km

Figure 1.1 General map showing location of slide area.

the west valley wall of the Battle River about 0.75km southeast of the South Slide. At this time, the scarp height had grown to 3m from the 0.5m height originally observed in May, 1980 by Mokracki (1982, p.16). This scarp has since increased to about 18m high and to about 260m long in July, 1990. This slope movement was subsequently termed the 80 Slide by Mokracki but is renamed the East Slide in this thesis considering its geographical position.

Collectively, the landslides have been referred to as the Edgerton Landslides by Mokracki (1982).

1.2 A review of research in the area

From the time that major slope movement was first observed in 1974, the landslides have been studied by personnel from the Department of Civil Engineering, University of Alberta. As part of the field program, two survey lines were established down the South Slide and one survey line down the East Slide. To study the surface movements of the slide area, a series of control points were established through the survey lines. The initial topographic surveys were performed in 1975 and the area has been surveyed periodically. Another survey line was established down the North Slide in 1987. These survey lines were used for the profiles of the landslides in this study (Chapter 5).

The movement of the area has been monitored by ground surveying using an electronic distance measuring instrument from 1990 (Peterson, 1992).

Large scale air photographs have been taken since 1986 to analyze the development of the Edgerton landslides. The dates of these airphotos and their scales are shown in Table 3.1.

Several results were obtained by the research of Tweedie (1976, p.100-104).

" 1. The North and South slides are the continuation of a retrogressive series of slides which have resulted in the present slopes. The rupture surfaces have been controlled by bedding, especially weak bentonitic clay shale layer, because the toe of the North Slide cropped out almost half way up the valley wall.

2. The slope indicator data, coupled with the results of the stability analysis indicate that the sliding material is moved along an essentially planar rupture surface, dipping at about 4.5° to the northeast.

3. Results of stability analyses, performed on the South Slide, suggest that residual strength parameters are being mobilized along the major portion of the horizontal part of the rupture surface, with peak angles of shearing resistance, but essentially zero cohesion in the scarp materials.

4. The gradual loss of cohesion coupled with a high spring runoff were the major cause of failure."

Mokracki (1982, p.70-71) showed

" 1. The South Slide is typical of translational slide behavior.
2. An intermediate internal shear zone exists within the overall South Slide mass. The existence of an intermediate shear zone within the overall slide mass may be a direct consequence of stronger material existing along the presumed rupture plane.
3. The apparent velocity of the South Slide appears to be controlled somewhat by the amount of surface runoff within the study area.
4. Results of the stability analyses, performed on the East Slide, suggest that the combination of peak angles of shearing resistance with zero cohesion along the scarp coupled with residual angles of shearing resistance and zero cohesion acting along the rupture surface results in a factor of safety near unity."

The research related to the geology in the area is reviewed in chapter 2.

1.3 Scope of investigation

The three landslides, which have been collectively termed the Edgerton landslides, are located at longitude 110°29'W, latitude 53°01'N on the gently sloping west valley wall of the Battle River. The height of the slope of the valley wall above river level is about 85m. The volume of the displaced mass is about 1.4 million cubic metres according to the calculation suggested by the International Geotechnical Societies' UNESCO Working Party on World Landslide Inventory (1990) (Table 1.1).

From the time that major slope movement first occurred in 1974, the landslide has grown in area and continues to grow. A new scarp formed in the main body of the displaced material of the North Slide and the area was greatly disturbed even though the North Slide scarp is stable. The toe of the East Slide moved down the slope and the toes of the North and the South Slides advanced.

Eight sets of airphotos which were taken in different years were interpreted to analyze the development of the landslides (Chapter 3). Detailed field mapping was done during the summer in 1990 to observe the study area more closely. The features related to the landslides were measured using a tape and a Brunton compass and were drawn on overlays on the airphotos using symbols (Chapter 4).

Three survey lines were established down the slide area. The initial topographic surveys were performed in 1975 and the

Table 1.1 Landslide Report

	North Slide	South Slide	East Slide
Locality	Edgerton, Alberta, Canada		
Position	Latitude 53° 01' 00"		
	Longitude 110° 29' 22"		
Type	Rock Slide - Debris Slide		
L_d (m)	276	287	138
L (m)	287	292	150
W_d (m)	168	120	240
D_d (m)	30	20	20
Volume (m^3)	696000	344000	331000
Total (m^3)	1371000		

Notes: L_d; Length from the tip of the displaced material to its top.

L; Total length from the tip to the crown.

W_d; Maximum width of the displaced mass.

D_d; Thickness of the displaced material.

area has been surveyed periodically. These survey lines were used to get the profile of the landslides and movement vectors of control points in this study (Chapter 5).

Alberta Environment's Development and Operations Division undertook a drilling program for information on the geology of the site and samples to determine the engineering properties of the rock. Direct shear tests, consolidation tests, and Atterberg limit tests were conducted at the Division's Geotechnical Laboratory using the core samples (Chapter 6). Stability analyses used the results of the direct shear tests to investigate the landslides (Chapter 7).

The purpose of this investigation was, therefore,

1. to analyze the landslides development from airphotos;
2. to obtain the engineering properties of materials along the rupture surface;
3. to propose a mechanism of movement using the interpretation of airphotos, field mapping, and laboratory tests;
4. to enhance predictive techniques for the movement of slopes on clay shale bedrock;
5. to document changes of landslides since 1982;
6. to produce the first geomorphological map of the landslides;
7. to investigate how the landslides have interacted with one another over time; and

8. to record the results of 2 new boreholes drilled by Alberta Environment behind the South and the East Slides.

Chapter 2

Description of the Site

2.1 Geologic History

The Upper Cretaceous strata of east-central Alberta and west-central Saskatchewan is characterized by large-scale intertonguing of nonmarine and marine sediments. The nonmarine tongues are thick in the west, thinning to the east; the marine tongues are thin in the east and thicken westward. The fact that the overall pattern of sedimentation during Judith River deposition was marine and that much of the formation is of nonmarine origin, suggests that the rate of supply of sediment exceeded the rate of subsidence of the seaway, and that the deltas, which coalesced to form the Judith River alluvial plain, built seaward more quickly than waves and currents removed and distributed the detritus (McLean, 1971).

Toward the end of Upper Cretaceous time, the sea retreated completely and deposition of continental sediments continued for some time. In latest Cretaceous and earliest Tertiary(Paleocene) times, broad uplift took place throughout the plains of western Canada accompanied by deep erosion (Webb, 1951). Parts of the Upper Cretaceous and all of the Tertiary sediments were removed from the study area by erosion.

During late Pleistocene time a Keewatin-centered ice sheet overran most of Alberta, advancing generally from the north-northeast (Pawluk and Bayrock, 1969, p.4). As a result of this glaciation, the study area is now covered by a veneer of glacial deposits.

After the retreat of the Pleistocene glaciers about 10,000 years ago, erosion by streams and rivers has taken place, resulting in deeply incised valleys through the glacial deposits and Cretaceous bedrock. This process has been accompanied by much landslide activity through the Battle River valley which has gradually flattened the valley slopes towards their stable angles.

2.2 Geology

2.2.1 Surficial Geology

Bedrock of Late Cretaceous age directly overlain by till can be observed in the scarp of the South Slide in the study area. The till is highly oxidized, columnar jointed, and on average about 5m thick. The till composition largely reflects that of underlying or nearby strata because most of the Alberta till material was locally derived (Pawluk and Bayrock, 1969, p.4).

Pawluk and Bayrock (1969) made mineralogical and physical contour maps for Alberta tills. According to the contour maps, the average till composition of the study area was 30-40% sand, 30-40% silt, and 20-30% clay, the clay fraction containing up to 40% montmorillonite.

The gravel content of the till is less than 5%, and is derived from the Canadian Shield, and from post-Cretaceous, preglacial gravels which overlie Cretaceous bedrock in scattered portions of the Alberta plains. The gravel portion of the till contained from 30 to 50% quartzite pebbles (Bayrock, 1967, p.5).

Plastic limits and liquid limits for the till in the study area ranged from 13 to 19% and 20 to 37% respectively (Chapter 6). When the liquid limit values are plotted combined with the plasticity index the till of the study area is classified as low to medium plastic soil according to the Unified Soil Classification System. The activity of the till in the study area is about 0.46, inactive (Chapter 6). Boulton and Paul (1976) suggested that the Atterberg limits served as good quantitative indicators of the fundamental properties of the debris which was deposited as till. According to Boulton and Paul, the samples with liquid limits above 22-24 fit relatively closely to a straight line (T-line) parallel to and somewhat above the A-line of Casagrande. Samples below a liquid limit of 22-24 fall well below the line (Fig. 2.1). When depositional and post-depositional processes produce a

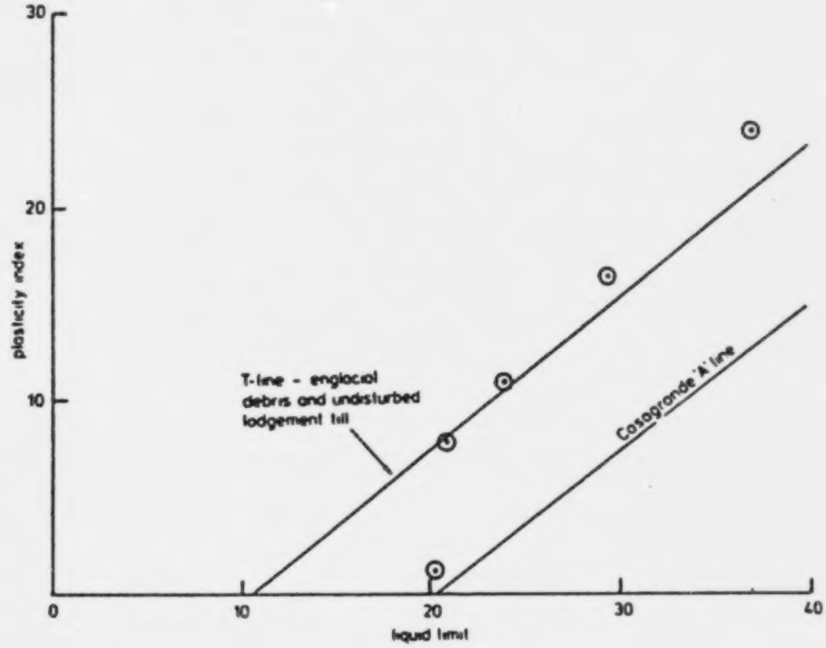


Figure 2.1 Liquid limit/plasticity index plot for tills.

grading which is substantially different from that of the parent englacial debris, tills move away from the T-line. The till in the study area fits closely to a T-line, which suggest that the till has undergone little or no change in grading during the depositional process, i.e., unaltered lodgement till (Fig. 2.1).

Colluvial materials originating from old and recent landslides cover the slopes of the river valley. Plastic limits and liquid limits for the colluvium range from 14 to 19% and 40 to 53% respectively. The activity calculated for the colluvium ranges from 0.71 to 1.00, which are classified as normal (Chapter 6).

Shetsen (1990) mapped the stagnation moraine of the prairie level above the study area as hummocky topography moderately to weakly developed.

2.2.2 Bedrock Geology

The bedrock geology of the study area was investigated by Hume (1924), Allan and Rutherford (1934), Hume and Hage (1941), Nauss (1945), Warren and Hume (1947), Shaw and Harding (1949), Nichols and Wyman (1969), and McLean (1971). The bedrock of the area was mapped by Hume (1924), Crickmay, Hume and Hage (1941), and Shaw and Harding (1949). The bedrock consists of interbedded sandstone, siltstone and claystone, and thin coal seams of late Cretaceous age. The rocks are poorly indurated and dip at less than one degree to the southwest.

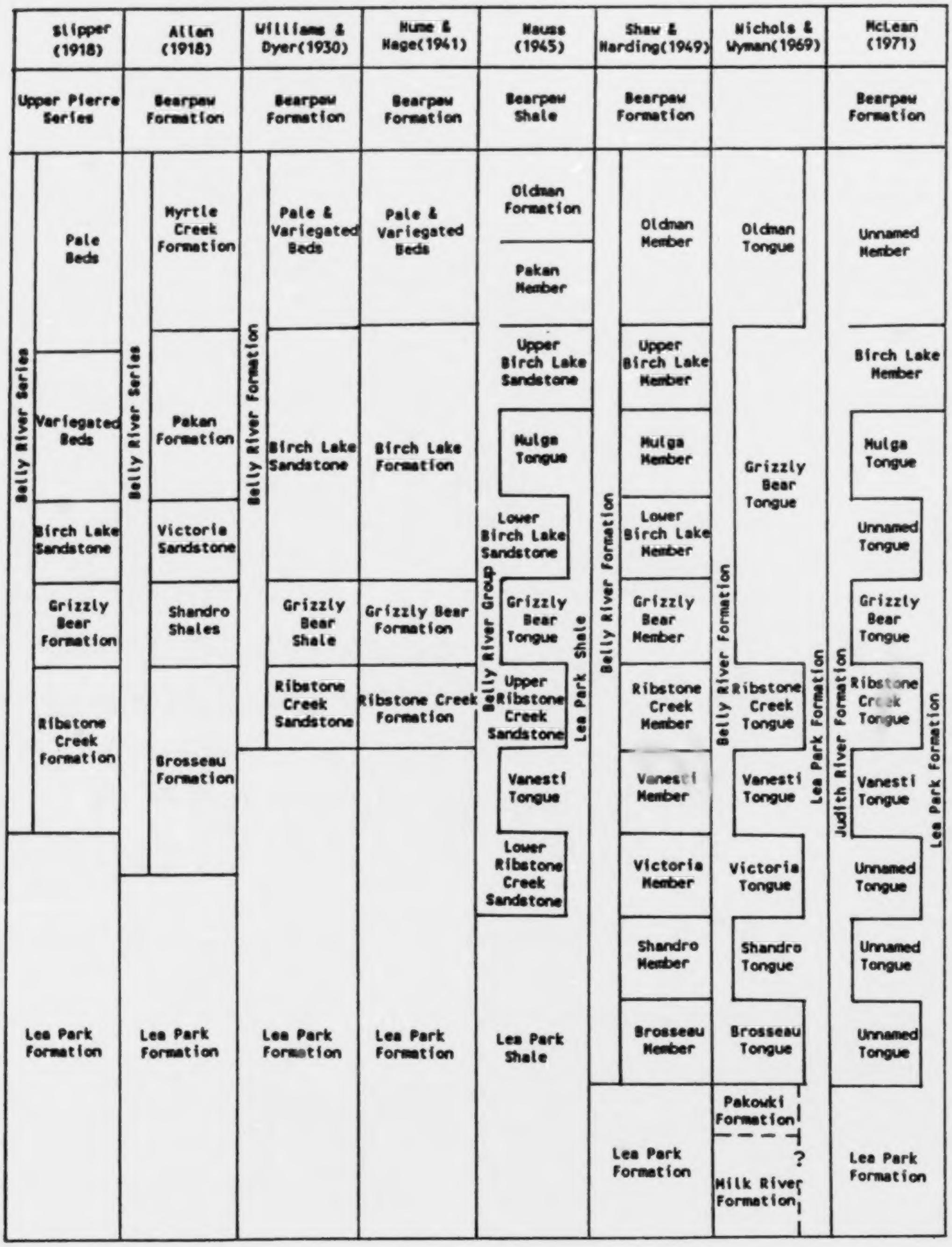
Hume (1924) mapped the bedrock of the study area, based on the nomenclature suggested by Slipper (1918), (Table 2.1). The Lea Park Formation (Allan, 1918) named marine shales cropping out in the vicinity of Lea Park on the North Saskatchewan River. The formation is a uniform series of gray, silty shales with local intercalations of sandy shale, ironstone concretionary bands, and bentonite.

Slipper (1918) and Allan (1918) determined the Upper Cretaceous stratigraphic succession in the vicinity of Viking and along the North Saskatchewan River between Edmonton and Battleford respectively. Both workers used the term Belly River Series for the beds above the Lea Park Formation and below the Bearpaw Formation. However, the formation names that they used are entirely different.

Hume and Hage (1941) did not group the formations into the Belly River Series although they used same formation names originated by Slipper (1918).

Nauss (1945) revised the nomenclature that had been used since the time of Slipper (1918) based on subsurface data and

Table 2.1 Lithostratigraphic nomenclature of Belly River in east-central Alberta.



Slipper (1918)	Allen (1918)	Williams & Dyer(1930)	Hume & Hage(1941)	Nauss (1945)	Shaw & Harding(1949)	Nichols & Wyman(1969)	McLean (1971)
Upper Pierre Series	Bearpaw Formation	Bearpaw Formation	Bearpaw Formation	Bearpaw Shale	Bearpaw Formation		Bearpaw Formation
Belly River Series	Belly River Series	Belly River Formation		Belly River Group Lea Park Shale	Belly River Formation	Belly River Formation Lea Park Formation	Judith River Formation Lea Park Formation
Pale Beds	Myrtle Creek Formation	Pale & Variegated Beds	Pale & Variegated Beds	Oldman Formation	Oldman Member	Oldman Tongue	Unnamed Member
				Pakan Member			
Variegated Beds	Pakan Formation	Birch Lake Sandstone	Birch Lake Formation	Upper Birch Lake Sandstone	Upper Birch Lake Member	Grizzly Bear Tongue	Birch Lake Member
				Mulga Tongue	Mulga Member		Mulga Tongue
Birch Lake Sandstone	Victoria Sandstone			Lower Birch Lake Sandstone	Lower Birch Lake Member		Unnamed Tongue
Grizzly Bear Formation	Shandro Shales	Grizzly Bear Shale	Grizzly Bear Formation	Grizzly Bear Tongue	Grizzly Bear Member		Grizzly Bear Tongue
Ribstone Creek Formation	Brosseau Formation	Ribstone Creek Sandstone	Ribstone Creek Formation	Upper Ribstone Creek Sandstone	Ribstone Creek Member	Ribstone Creek Tongue	Ribstone Creek Tongue
		Lea Park Formation	Lea Park Formation	Vanesti Tongue	Vanesti Member	Vanesti Tongue	Vanesti Tongue
Lea Park Formation	Lea Park Formation			Lower Ribstone Creek Sandstone	Victoria Member	Victoria Tongue	Unnamed Tongue
				Lea Park Shale	Shandro Member	Shandro Tongue	Unnamed Tongue
					Brosseau Member	Brosseau Tongue	Unnamed Tongue
					Lea Park Formation	Pakowki Formation	Lea Park Formation
						? Milk River Formation	

detailed field work. He used the term tongue instead of the term formation. He recognized a marine shale tongue in the middle of the Birch Lake sandstone and another in the Ribstone Creek Formation. He used the name Mulga for the former shale tongue, and Vanesti for the latter. He also recognized a marine shale tongue, the Grizzly Bear Tongue, between the Lower Birch Lake sandstone and the Upper Ribstone Creek sandstone. He observed that as the Lower Ribstone Creek sand thins out toward the east the Vanesti, Grizzly Bear, and Mulga Tongues join with the Lea Park to form one inseparable body of shale. He used Allan's (1918) name Pakan instead of Slipper's (1918) name Variegated beds. He applied the name Belly River Group to include all of the sand units - Oldman Formation, Pakan Member, Upper and Lower Birch Lake sandstone, and the Upper and Lower Ribstone Creek sandstone. The intervening shale tongues were included in the Lea Park Shale (Table 2.1).

Shaw and Harding (1949) studied the Belly River and Lea Park Formations in east-central Alberta by means of lithologic, microfaunal, and electric-log data. They employed the name Belly River as a formation name. The marine shale tongues which interfinger with the deltaic sands of the Belly River, classified as Lea Park shale by Nauss (1945), were arbitrarily placed as members of the Belly River Formation. Their uppermost member, the Oldman, included the Pakan beds of Allan (1918) and Nauss (1945) and the equivalent Variegated beds of Slipper (1918). They pointed out that the division of the Pale and Variegated beds by Slipper (1918) was considered impractical by subsurface geologists and, therefore, should be abandoned.

Nichols and Wyman (1969) obtained information about the Belly River and Lea Park Formations in east-central Alberta from the study of the type localities and 34 wells. They suggested, as had Nauss (1945), that the members of the Belly River and Lea Park Formations should be called tongues because the members extend beyond the formations. They warned that the shale of Belly River Formation may be confused with that of the Lea Park Formation because of lithologic resemblance. Because the Belly River and Lea Park Formations interdigitate across the area, they suggested that the individual names of each tongue and their respective formations should be employed together for clarity and a coherent geologic picture.

The most recent revision of nomenclature is that of McLean (1971), who studied upper Cretaceous formations in the Interior Plains. He suggested that the name Judith River should be employed instead of the name Belly River because of the precedence and clarity of the name. He did not use the name Oldman because the distinction between Oldman beds and Foremost beds is too vague. He also left five members unnamed because the names which Shaw and Harding (1949) employed were incorrectly applied. The name Judith River is employed in this thesis instead of the name Belly River following McLean's (1971) suggestions.

The bedrock units of the study area along the river valley, mapped by Crickmay, Hume, and Hage (1941), were all of late Cretaceous age; these were the Birch Lake Formation, Grizzly Bear Formation, and Ribstone Creek Formation. These formations are equivalent to Birch Lake Member, Mulga Tongue, Unnamed Tongue, Grizzly Bear Tongue, Ribstone Creek Tongue, Vanesti Tongue, and Unnamed Tongue of McLean's (1971) nomenclature (Table 2.1).

The predominantly non-marine Judith River Formation and the marine Lea Park Formation interfinger in the study area. To draw boundaries between these rock units is very difficult because of lithologic resemblance, scarcity of outcrops, weathering of the outcrops, and lack of paleontologic data. The bedrock of the study area is exposed in the scarps of the three slides, in the minor scarp at the graben area below the North Slide, in the flank of the North Slide, in the minor scarp below the South Slide, and in the bed of Battle River. Those positions are marked on Fig. 4.1. Most of the exposed bedrock is severely weathered. The borehole logs of the study area combined with the observation of the outcrops are mainly used to correlate the bedrock of the study area. Table 2.2

Table 2.2 Physical characteristics of detrital units

Formation	Name	Thickness (M)	Description
Judith River	Birch Lake Member	0-15	Massive, buff-coloured, crossbedded sandstone, containing lenses of harder sandstone. Brackish water deposits. Thin-bedded sand and shale. Oyster beds. Plant fragment.
Lea Park	Mulga Tongue	0-14	Massive, dark-grey marine shale with fine silt lenses and without plant remains. The lower contact is sharp, the upper gradational.
Judith River	Unnamed Tongue	0-35	Basically same as the Birch Lake Member.
Lea Park	Grizzly Bear Tongue	0-43	Dark, blue grey, marine shale containing ironstone and sandstone nodules. Some beds of yellow, incoherent sandstone.
Judith River	Ribstone Creek Tongue	0-37	Greenish-yellow, massive, soft sandstone at top, green and carbonaceous shale and coal seams, light grey sandstone at base, oyster beds.
Lea Park	Vanesti Tongue	0-43	Grey shale and silty shale with thin lenses of fine-grained sand.
Judith River	Unnamed Tongue	0-29	Basically same as the Ribstone Creek tongue.

shows the descriptions of each tongue. The table is made from the reports of Slipper (1918), Hume and Hage (1941), Nauss (1945), and Shaw and Harding (1949).

Sandstone outcrop about 0.2m thick is overlain by the till at the North Slide scarp. This sandstone may be correlated with Birch Lake member according to the geologic map of Kitscoty, Alberta (Crickmay, Hume, and Hage, 1941).

The clay shale which are exposed at the scarp faces of the three main slides can be correlated with the Mulga Tongues. However, this correlation is not certain because the typical Mulga Tongue does not contain gypsum crystals.

Clay shale which contains a sandstone nodule is exposed at the minor scarp near the pond below the North Slide. The elevation of the outcrop is about 610m. This outcrop may be correlated with the Grizzly Bear Tongue. The upper contact with the Unnamed Tongue which is equivalent to Lower Birch Lake sandstone of Nauss (1945) is not obvious because the outcrop of the Unnamed Tongue is not found at the study area. The lower contact with the Ribstone Creek Tongue is decided from the characteristics of the Ribstone Creek Tongue which contains oyster beds and coal seams. The elevation of the boundary is about 604m at the borehole ES-1 (Chapter 5). This elevation is approximately halfway between the river and the valley crest. However, the lithology of this section is not typical Ribstone Creek tongue because the borehole samples of the section and an outcrop at the flank of the North Slide which are at the elevation of about 600m consist of interbedded clay shale and sandstone. The lower contact with the Vanesti Tongue is not obvious in the borehole samples.

Sandstone is observed in the bed of the Battle River. This sandstone can be correlated with the Unnamed Tongue which is equivalent to the Lower Ribstone Creek sandstone of Nauss (1945).

The rupture surface of the South Slide was located at the bentonitic clay shale near the upper boundary of "white fossil layers" from the slope indicator study (Tweedie, 1976, p.50). This is equivalent to the base of the Grizzly Bear Tongue. Therefore, slope movement is mainly taking place through the Grizzly Bear Tongue in the South Slide. The rupture surfaces of the North and East Slides may be located mainly at the Ribstone Creek Tongue according to the profile study of the area (Chapter 5).

Paleontologic data, electric-log data, and more complete recovery of core from bore holes are needed in order to accomplish more accurate geologic correlation in the study area.

2.3 Climate

The climates of Canada can be divided into seven major groups as follows: Pacific Canada, Cordilleran Canada, the Prairie region, the Great Lakes-St Lawrence region, Atlantic Canada, the Arctic region, and Boreal region (Hare and Thomas, 1979, p.93). The study area is in the Prairie region. A continental type of climate prevails in the area. This region experiences bitterly cold winters, short but warm summers, and a light precipitation regime. The climate is subhumid. Temperature changes from summer to winter are greater on the Prairies than in any other part of Canada (Hare and Thomas, 1979, p.101).

Precipitation records for Paradise Valley, latitude 53°07'N, longitude 110°21'W, elevation 660m A.S.L. from 1962 to 1991 are listed in Appendix 1. These records were obtained from the meteorology reading room in the Department of Geography, University of Alberta. Paradise Valley is located approximately 10km east of the landslide area. Based on the 30 years of records from 1951 to 1980 the average annual rainfall is 427.1mm.

Fig. 2.2 shows precipitation records for Paradise Valley from 1962 to 1991. The precipitation in 1974 was not higher

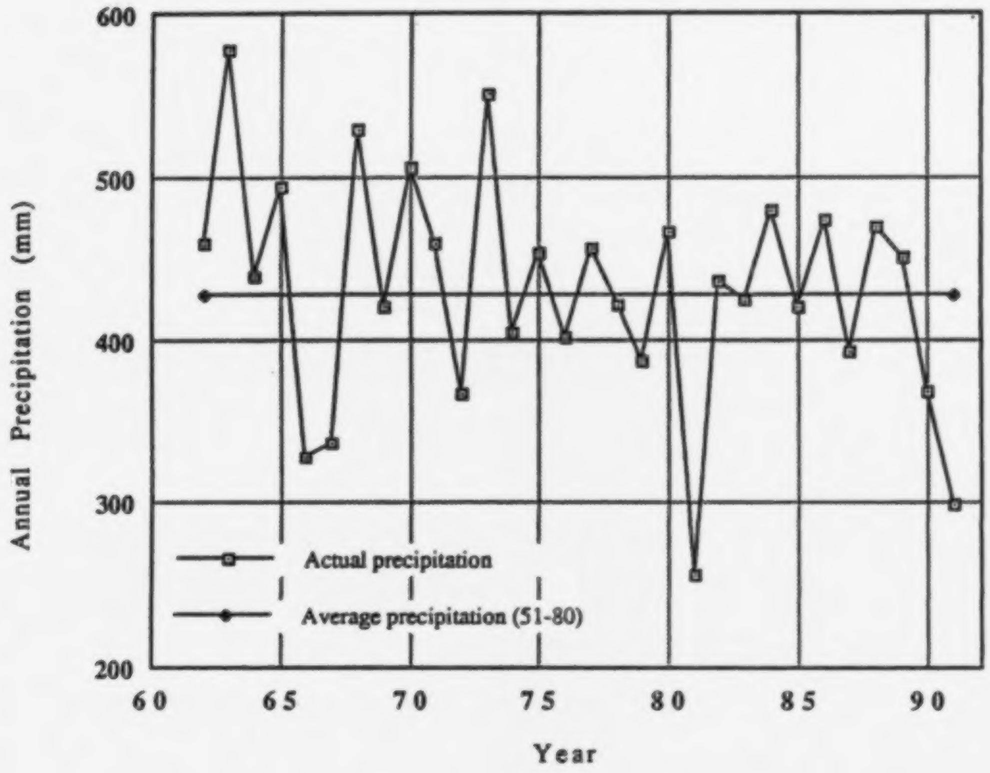


Figure 2.2 Precipitation record of Paradise Valley, Alberta

than average annual rainfall. However, the precipitation (119.7mm) between November 1973 and February 1974 was higher than those of the previous 11 years (average, 83.3mm). Therefore, the pore pressures might be high compared to the previous 11 years during the spring, 1974. Locally pore pressures may be elevated by the removal of the trees (documented in the 1949 airphotos, Fig. 3.2). This would reduced evapotranspiration (Gray, 1970) and allow wind blown snow to accumulate below the scarp.

Chapter 3

Analysis of Landslide Development from Airphotos

3.1 General

The three landslides which have been collectively termed the Edgerton Landslides are located on the west wall of the Battle River valley, approximately 48km northeast of Wainwright, Alberta. The scarps of the earlier two slides follow roughly a north-south direction, so the slides have been conveniently termed the North Slide and the South Slide by Tweedie (1976). The third and most recent slide has been termed the 80 Slide by Mokracki (1982) but is named here the East Slide to reflect its location with respect to the other two slides.

From the time that major slope movement first occurred in 1974, the landslides have grown in area and continue to grow. To get the information of pre-landslide landscape and to analyze the development of the Edgerton landslides, aerial-photograph interpretation techniques are used in this chapter. Drainage, surface features related to the landslides, change of slope angles, and human activities near the landslide areas are observed and recorded.

All the publically available airphotos, eight sets which were taken in 1949, 1963, 1975, 1981, 1986, 1987, 1989, and

1991, were interpreted to analyze the evolution of the Edgerton landslides. The years and dates of these airphotos with their scales are summarized in Table 3.1.

Wild AVIOPRET APT1 photo-interpretation stereoscope (Heerbrugg, Switzerland) with 10X magnification of the eyepieces was used to interpret these airphotos. The optics provide a good overall view of the area to be interpreted, with a maximum field of view (at 3.1X magnification), whilst questions of detail could be speedily clarified up to 15.5X magnification (continuously variable).

The information contained in the photographs were plotted on transparent sheets placed over the airphotos using symbols as described by Cruden and Thomson (1987, p.16-20). Since the airphoto sets which were taken in 1987 and 1991 do not have an airphoto which covers the whole study area, 4 and 2 airphotos (i.e., 4 and 2 overlays) are used for interpretation respectively.

To explain the changes of airphotos in a specific area effectively, the study area is divided into 12 areas using some standard points which were not moved by the landslides and each area is subdivided into 4 small equal areas. The 12 areas are numbered from left to right and from top to bottom consecutively and the small areas are named using A to D. If

Table 3.1 Airphoto Sets of the Edgerton Landslides

Year	Day	Time	Scale
1949*	September 13	Unknown	1:40000 **
1963	May 22	18:49	1:31680 **
1970*	August 3	16:15	1:80000 **
1975	July 27	Unknown	1:31680 **
1981	June 5	17:23	1:30000 **
1982*	May 10	15:47	1:60000 **
1986	October 11	18:03	1:4000
1987	October 21	17:24	1:2000
1989	October 26	17:15 17:26	1:4000 1:2000
1991	April 21	14:45 15:10	1:5000 1:2000

* Airphoto sets which were not used for detailed analysis.

** Six times enlargements of original scale airphotos are available.

the study area were divided into equal areas or active points were used as standard points to draw a grid it would difficult to explain the evolution of specific positions on the landslides effectively because of the differences in distortion between each airphoto set.

The locations of specific ground features are given by co-ordinates which were obtained using a method described by Norris(1972). The co-ordinates were determined with respect to the centre of the air photograph with the aid of a transparent, millimetre grid overlay (Fig. 3.1). The exact position was read from the photo to the nearest fifth of a millimetre and estimated to the nearest tenth. If this method is applied carefully, any point so designated on the photo can be recognized without ambiguity on the ground within a few metres (Norris, 1972). When correctly positioned, the intersection of the X and Y axis coincides with the centre of the photograph and a given point falls in one of the four quadrants. Then, measure the distance from the centre point using the transparent overlay. The positive X- and Y-directions are east and north respectively on vertical photos. For example, the co-ordinates of the point 1 are (3.00, 1.00) and those of the point 2 are (-1.00, -2.00) with respect to the origin. When the observed feature is large the centre point of the feature is used to locate the position. In order to use the grid overlay accurately, each overlay has fiducial

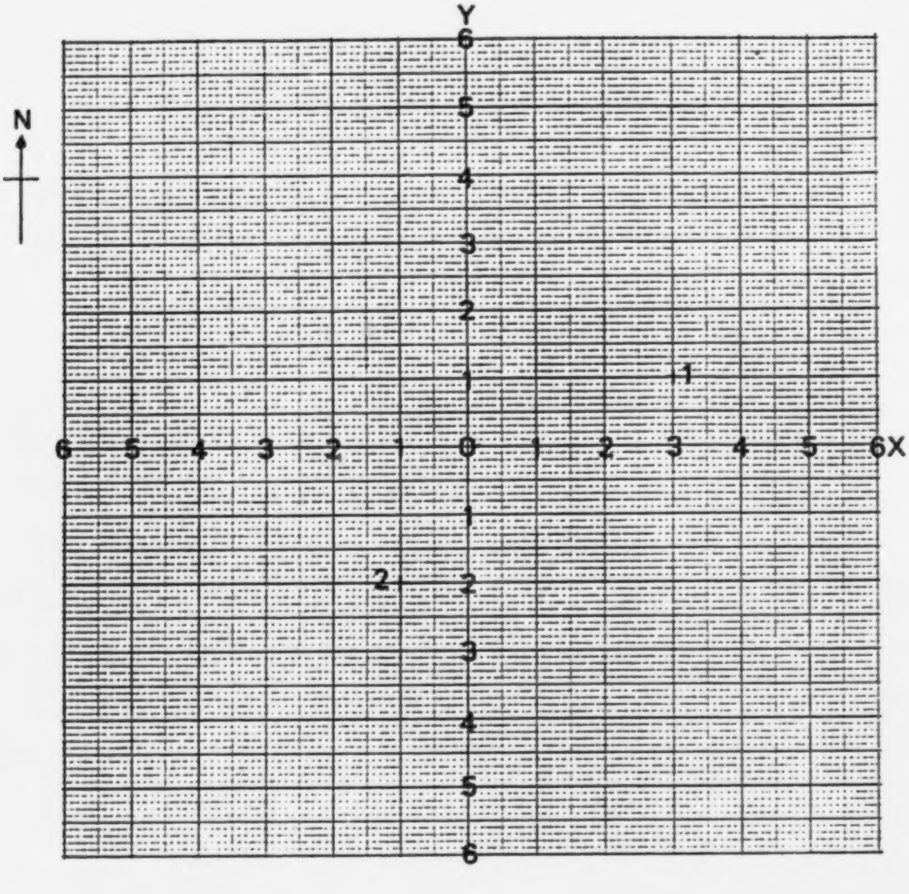

Y
X
N
6
5
4
3
2
1
0
1
2
3
4
5
6
1
2

Figure 3.1 Replica of millimetre grid. Numbers are distances in centimetres from origin.

marks except the blown-up airphotos. The reader can measure the distance from the centre point using a grid overlay or a ruler to determine the position of the feature which is explained.

Each airphoto set is discussed in the same way except the pre-landslide airphotos (1949, 1963); first, the scale of airphotos, effect of shadows, and quality of airphotos are described, and second, the changes of surface feature from previous airphotos are discussed from the scarps to the toes of the North Slide, South Slide, and East Slide.

The pre-landslide landscape of the study area is evaluated using 1963 airphotos. The 1949 airphotos are used only for the explanation of changes in land use near the North Slide scarp because other features are basically the same as those on the 1963 airphotos.

3.2 Evolution of landslides from airphotos

3.2.1 1949 airphotos

Original scale airphotos (1:40000) and airphotos which were enlarged six times were interpreted to analyze the study area. Because the quality of the 1963 airphotos is better than that of the 1949 airphotos and the basic surface features are the same in each, the 1963 airphotos were mainly used to analyze the study area before the landslide took place. One distinct feature of the 1949 airphotos is the area of trees about 650m behind the North Slide scarp at A and B areas, which had been removed in the 1963 airphotos (Fig. 3.2). The extent of the areas of trees were approximately 10 hectares. The A area is interpreted as being cultivated in the 1963 airphotos. The B area is cleared but not cultivated. The B area is under a crop in the 1970 airphotos.

3.2.2 1963 airphotos

Airphotos which were enlarged to six times the original scale of the airphotos (1:31680) were interpreted to analyze the study area before the landslide took place (Fig. 3.3). Since the airphotos were taken at 18:49 on May 22, the sun angle was low but it is not obvious on the airphotos. Several facts were observed even though the reproductions of the enlarged airphotos were not good.

1) Landslide topography along both sides of the river valley indicates ancient landslides. In areas 2 and 3, the uppermost part of the slope, the slope angle is steeper than the regional slope angle and changes suddenly, suggesting old landslide topography. Raised features observed at the position of the toe of the present East Slide in 7 and 8 suggest that the East Slide is the reactivation of an old landslide.

2) Since drainage can be closely related to the landslide, drainage channels were identified by the depression of the ground, vegetation, dark tone, and the slope angle. A

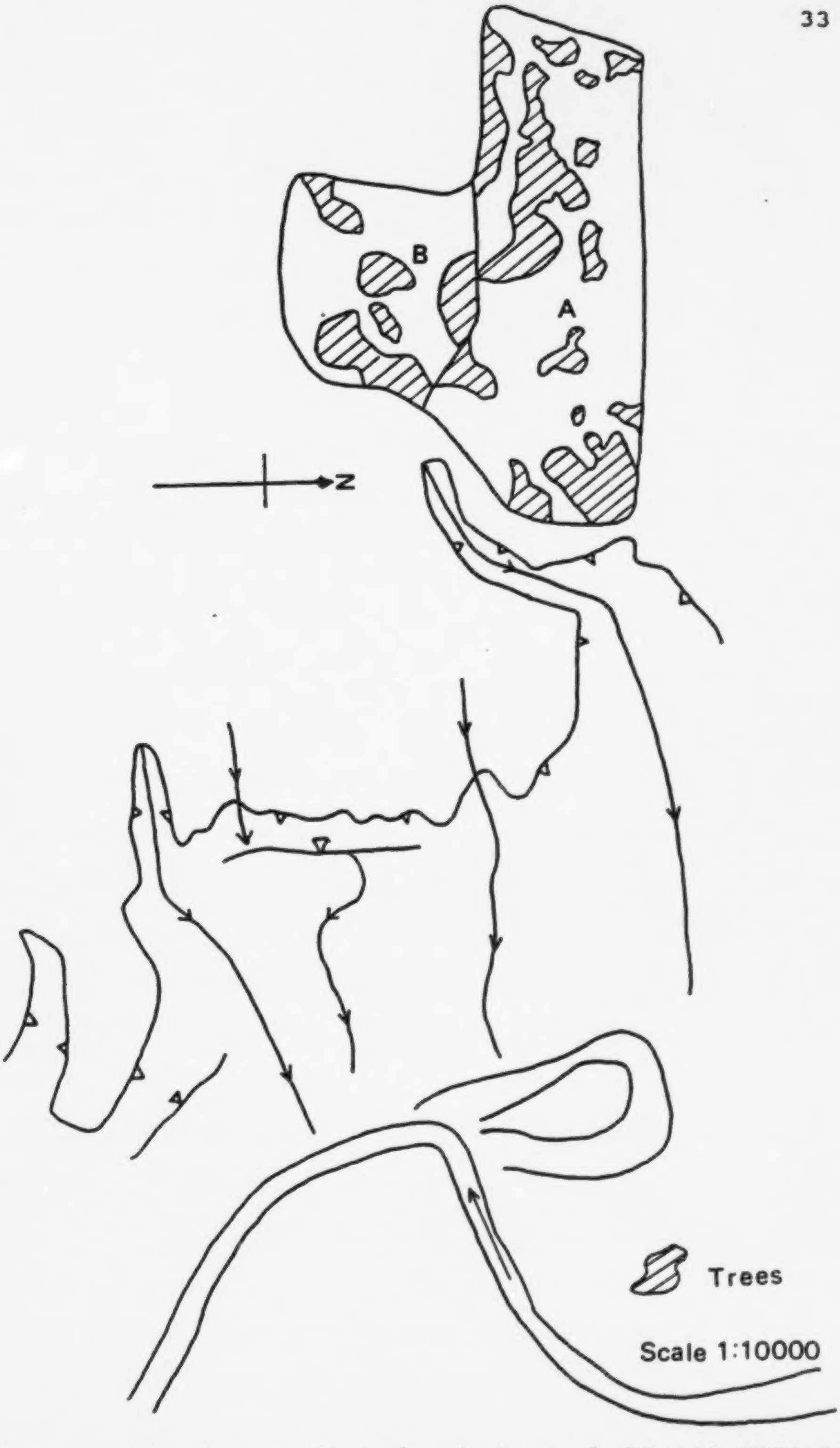
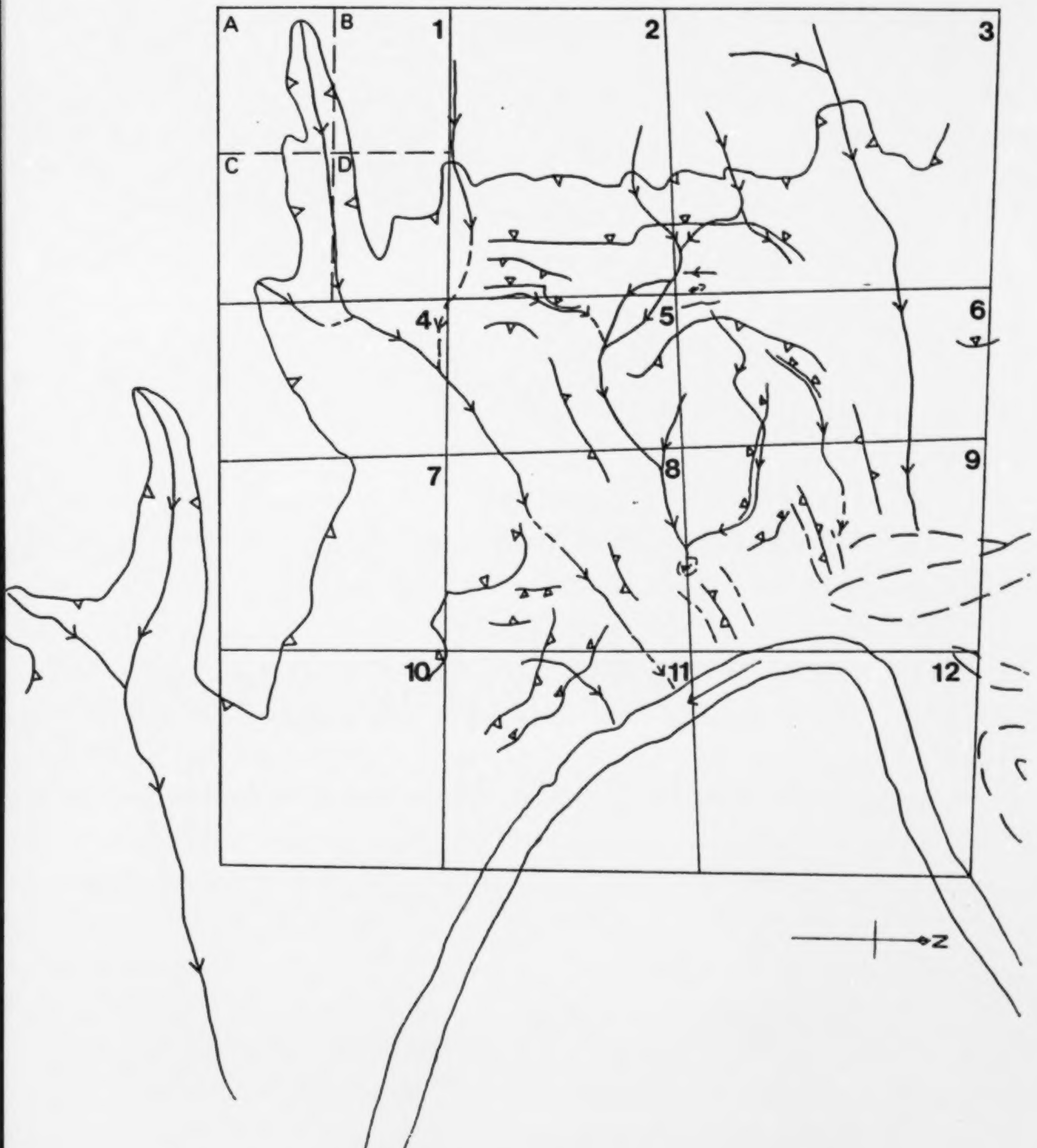

B
A
Z
Trees
Scale 1:10000

Figure 3.2 An overlay on the air photograph AS 143-5300-138 which was taken in 1949.

Figure 3.3 An overlay on the air photograph AS 860-37 which was taken in 1963. (Scale 6X 1:31680)


A
B
C
D
1
2
3
4
5
6
7
8
9
10
11
12
N

pond formed by the collection of water from the drainage channel in 8-D.

3) It is obvious that the south-facing slope is more thinly vegetated than the north-facing slope in 1, presumably because of its dryness.

4) The slope in 1,2, and 3 is bounded on both sides by large gullies which offer good drainage to both ends of the slope. It could be assumed that the water table is comparatively low at this site.

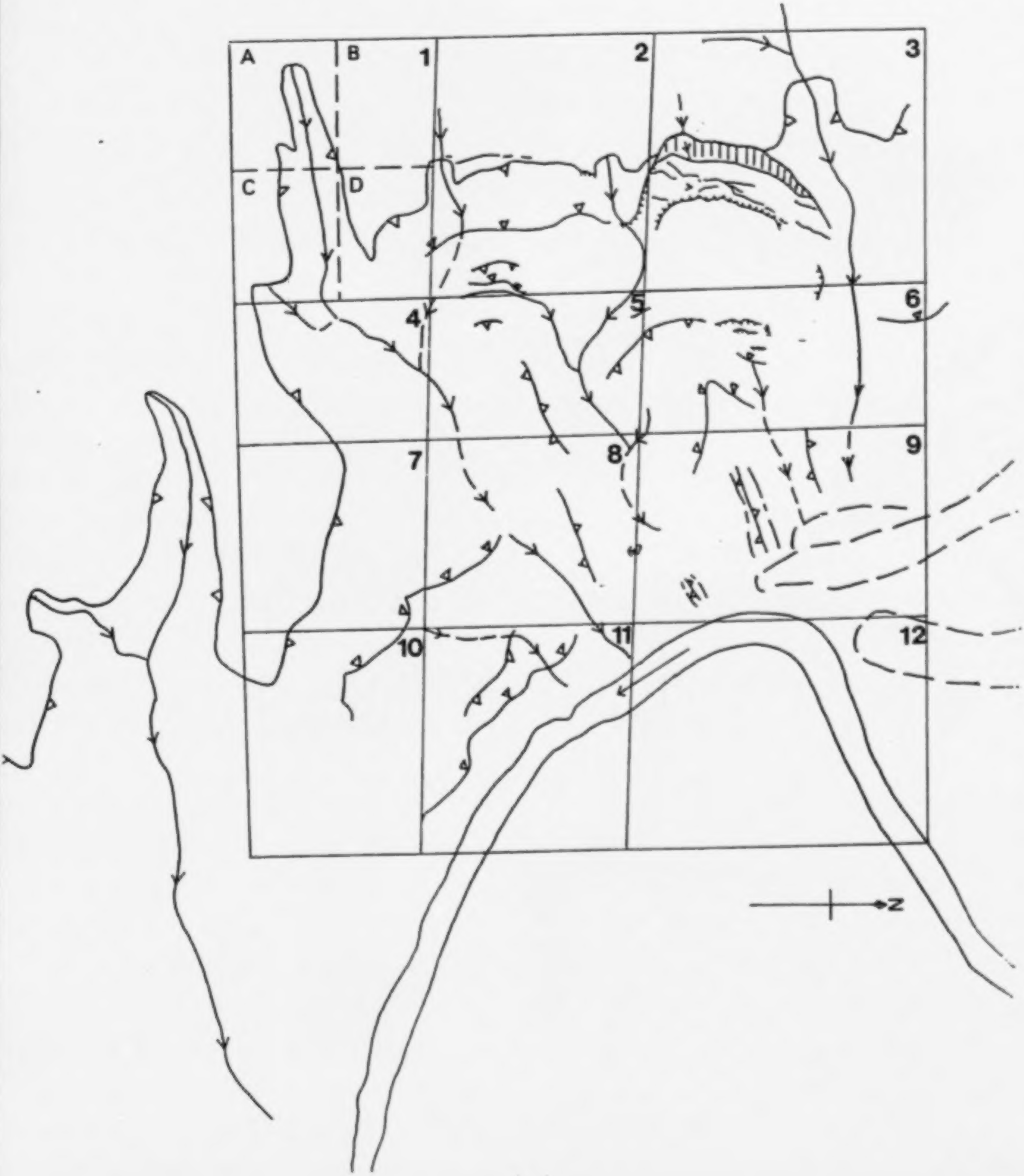
5) The river meanders along this section, and in fact an oxbow lake occurs in 9-D and 12-B.

3.2.3 1975 airphotos

Airphotos which were enlarged to six times their original scale (1:31680) were interpreted to analyze the study area (Fig. 3.4). The time of the day which the airphotos were taken is unknown. From the observation of shadow, the sun angle is high and the sun is located to the south-south-east. Since the sun angle is high the shadow does not affect the airphoto interpretation.

The scarp of the North Slide is visible in 3. The scarp was identified by the sudden break of the slope and vegetation-free slope face. Downslope of the North Slide scarp, another scarp has formed facing uphill. The block between these two scarps has moved downward and a graben has

Figure 3.4 An overlay on the air photograph AS 1418-Line 12-91 which was taken in 1975. (Scale 6X 1:31680)


A
B
1
2
3
C
D
4
5
6
7
8
9
10
11
12
N

formed. The block has several long cracks. These cracks were identified by linear vegetation-free areas. In 3-C, the black dot on the airphotos caused by the pond has disappeared because the slope angle changed due to the landslides and water infiltrated the cracks. Several scarps formed in 6-A and between 3 and 6. The scarp area in 6-A was regarded as the toe of the North Slide by Tweedie (1976).

Several cracks have formed to the south of the North Slide in 2-A.

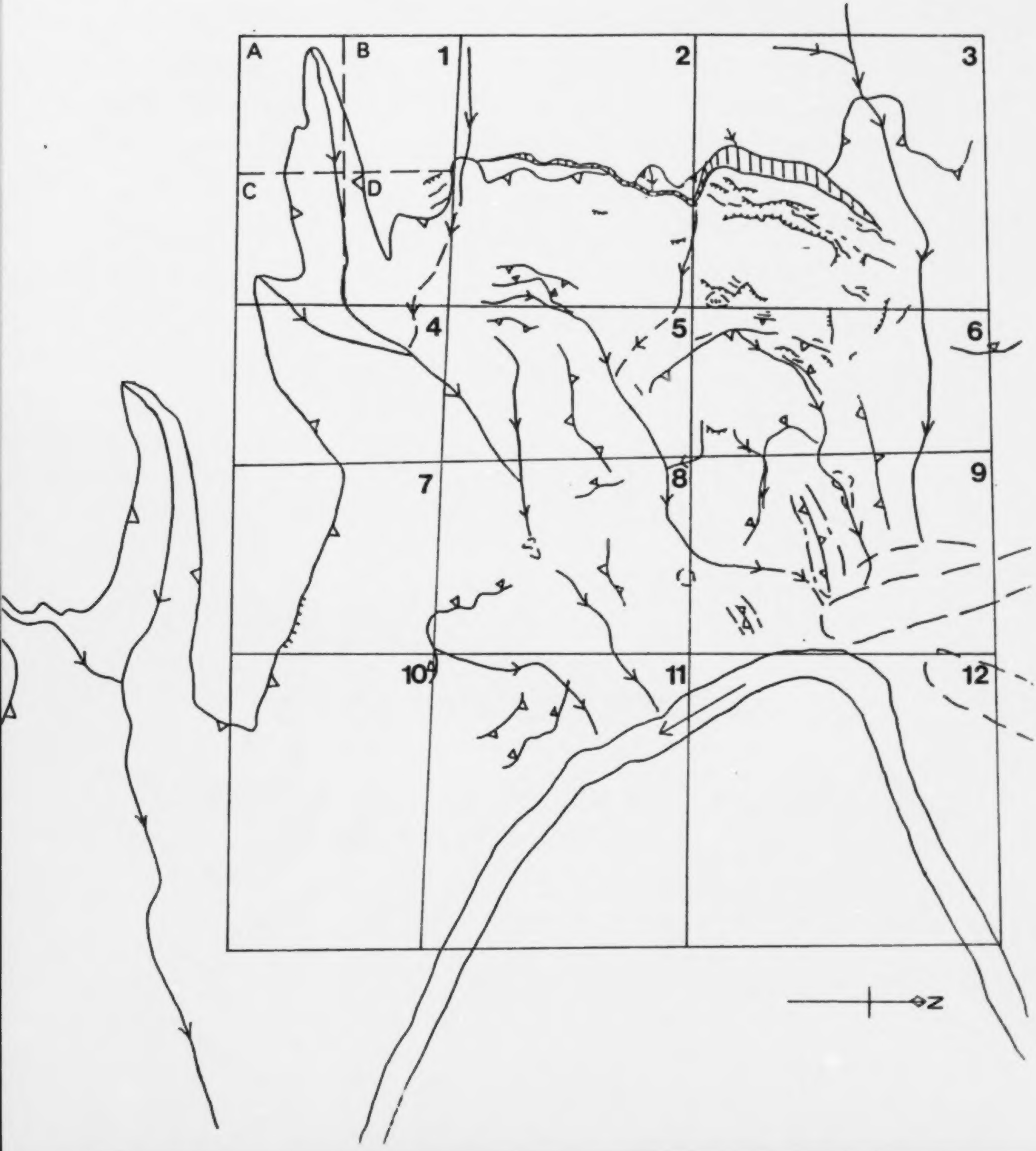
3.2.4 1981 airphotos

Airphotos which were enlarged to six times their original scale (1:31680) were interpreted (Fig. 3.5). The airphotos were taken at 17:23 on June 5. Shadows did not affect the airphoto interpretation because the sun angle was high.

In 3-A, the cracks developed as scarps because of the horizontal and vertical movement of the disrupted materials in the graben area of the North Slide. These scarps were facing downhill.

In 3-C, a new scarp formed parallel to the North Slide scarp. This slope movement is an advancing failure of the North Slide and may be caused by the uplift of the area due to the North Slide movement. A pond formed in 3-C. This pond

Figure 3.5 An overlay on the air photograph AS 2421-119 which was taken in 1981. (Scale 6X 1:31680)


A
B
1
2
3
C
D
4
5
6
7
8
9
10
11
12
Z

might be a sag pond formed by the change of slope angle due to the landslide movement in the area. A small scarp is visible in 6-C.

In 2, the scarp of the South Slide has developed from the cracks shown on the 1975 airphotos. The South Slide extended to the north and linked with the North Slide. A scarp has formed in 1-D, which is the south extension of the South Slide. In this area, two cracks formed.

In 8-B, the slope angle steepened due to the South Slide movement. In 8-D, the water in the pond dried. It may be caused by the change of slope angle around the pond due to the slope movement.

The scarp of the East Slide formed in 7-C. This scarp is identified by a well-defined linear feature which was not seen in 1975 airphotos. A surface drainage channel identified by the depression of the ground and vegetation formed in 11-A.

3.2.5 1986 airphotos

Original scale airphotos (1:4000) were interpreted to analyze the development of the landslides (Fig. 3.6). The airphotos were taken at 18:03 on October 11. Because of the shadow, the scarp of the East Slide and parts of the North Slide are not visible and the extension of the East Slide is

Figure 3.6 An overlay on the air photograph 366 which was taken in 1986. (Scale 1:4000)

C
10

not obvious. The long shadows obscure some cracks under the trees and in the graben in the North Slide.

In 3-C, the scarp is much more developed at (-3.60, 3.50) and two minor scarps formed behind the scarp. Many cracks, scarps, and bulges formed in 5-D, 6-A, and 6-C.

Several scarps developed from the cracks in 1-D. The South Slide lengthened to the south. A graben formed at (-6.00, -0.40) in 2-A. The antithetic scarp of the graben developed after the main scarp formed. Ritchie(1958, p.64) described the formation of a graben as follows:

> "Grabens do not form if the slump block has sheared on surface that approaches arc of circle; instead, they form on slump blocks that slide over a principal surface of rupture having a marked decrease in its curvature, causing greater horizontal movement for each unit of vertical offset in the centre portion of slide than in the head region."

From the above statement, the graben formed by the decrease in curvature of the rupture surface. This produces tension and, ultimately, rupture in the displaced material because of lack of support on its uphill side.

In 2-D, several scarps which face downhill formed at (-5.30, 0.98). Cracks formed in 2-D. In 5-C and 5-D, the toe of the South Slide developed at (-0.50, 0.68). Several cracks formed at the toe due to the uplift of the toe area. Some cracks which are not obvious in the previous airphotos are visible at (4.75, 1.65) in 11-B but the cracks may be related to old landslides because there is no sign of slope movements between the toe of the South Slide and these features (Fig. 3.6).

In 7, 8, 10, and 11, East Slide and toe of the East Slide are completely visible and some cracks formed. The outline of the toe of the East Slide is close to that of the old landslide in the 1963 airphotos.

3.2.6 1987 airphotos

Original scale airphotos (1:2000) were interpreted (Fig. 3.7, a-d). The airphotos were taken at 17:24 on October 21. Because of the shadow the scarp face of the East Slide, south parts of the North Slide scarp, and some cracks in the graben in the North Slide are not visible and the extension of the East Slide is not clear. Since the shadow is long, some cracks under the trees were obscured.

The antithetic scarp of the North Slide extended more parallel to the direction of the slope movement at (3.15, 3.17) in 3-C (Fig. 3.7, a). Movement on the minor scarp near the pond in 3-C was replaced by the movement of the small scarp at (3.72, 4.00) which existed behind it. In this case, the term retrogressive can be used as suggested by Varnes

Figure 3.7-A An overlay on the air photograph NW 39887-123 which was taken in 1987. (Scale 1:2000)

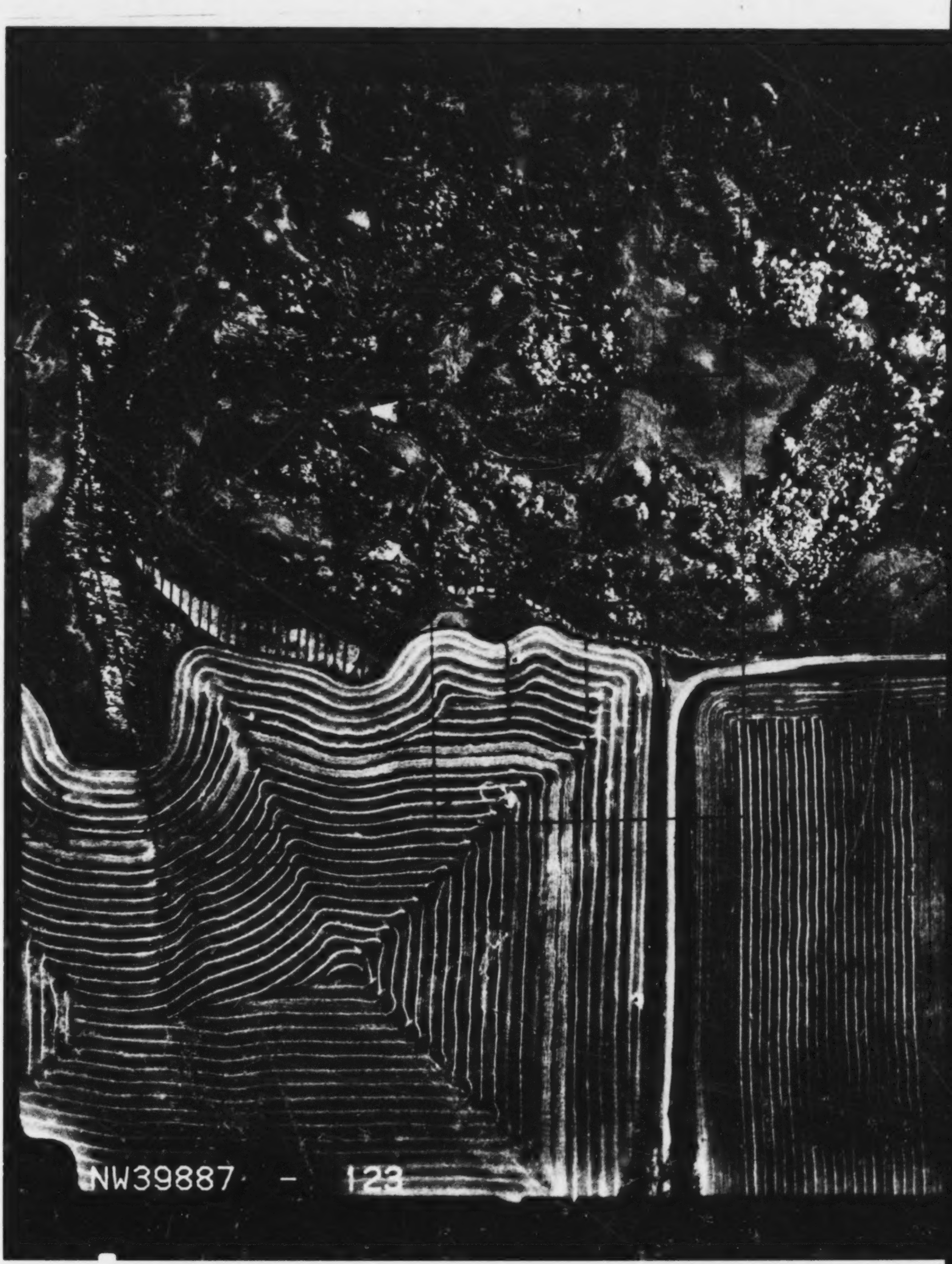

NW39887 - 123

Figure 3.7-B An overlay on the air photograph NW39887-117 which was taken in 1987. (Scale 1:2000)

C
D
11
NW39887

Figure 3.7-C An overlay on the air photograph NW39887-111 which was taken in 1987. (Scale 1:2000)

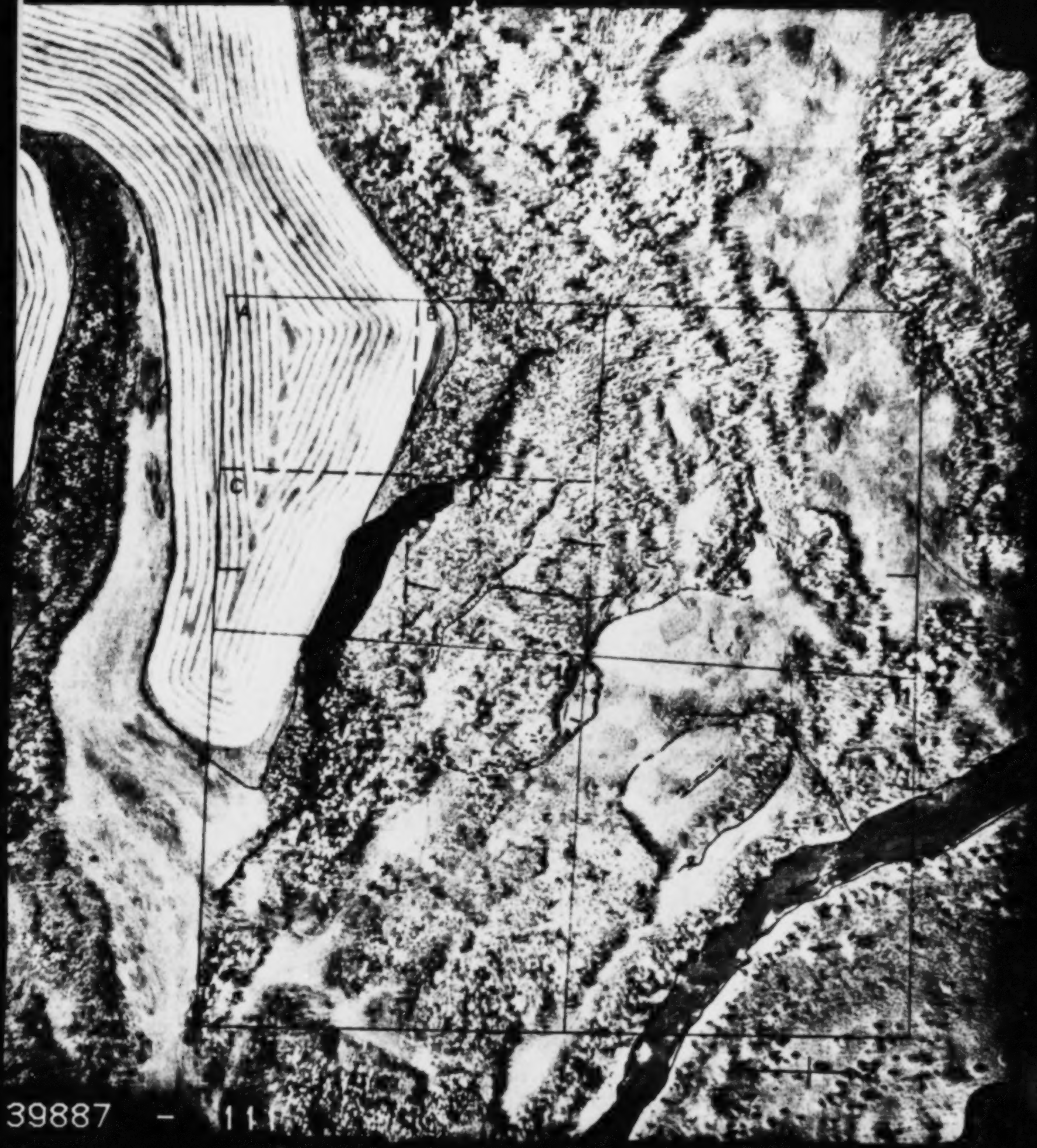
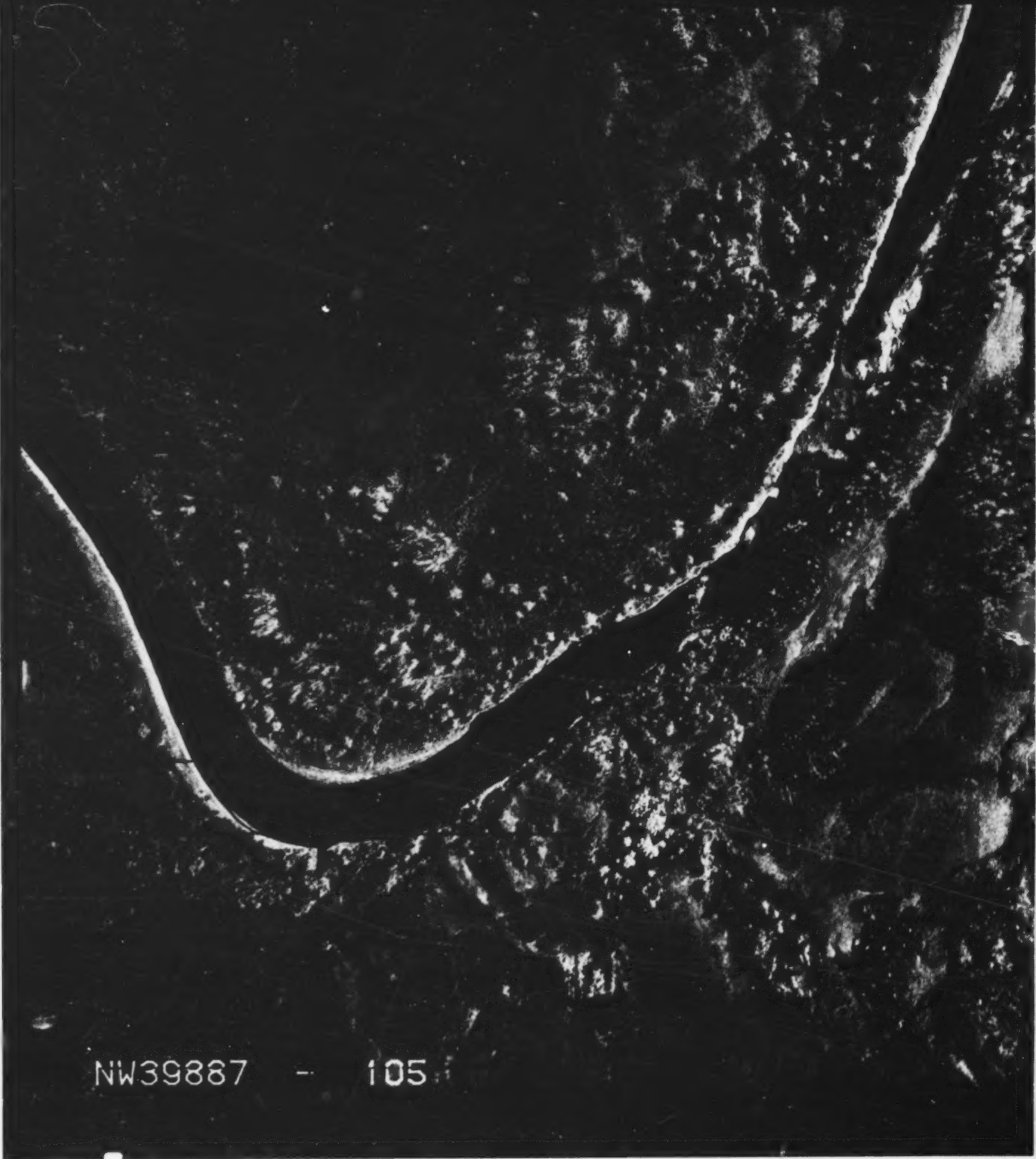

A
B
C
D
39887 - 11

Figure 3.7-D An overlay on the air photograph NW39887-105 which was taken in 1987. (Scale 1:2000)


NW39887 - 105

A

B

(1978, p.23). In 5-B, the scarps and cracks developed more. Many scarps have formed parallel and perpendicular to the direction of slope movement in 6-A and 6-C.

A graben has formed in 1-D (Fig. 3.7, b). Additional scarps formed in 2-D. New cracks have formed due to the South Slide movement in 5-C. Small cracks and scarps have developed parallel to the direction of slope movement in 8-B. In 11-B, scarps are visible at (8.90, 8.30) in the air photograph NW 39887-117 (Fig. 3.7, b).

In 8-C and 10-B, additional cracks have formed at the toe of the East Slide (Fig. 3.7, c).

3.2.7 1989 airphotos

Two different airphoto sets of original scale 1:2000 and 1:4000 were available to analyze the development of the landslides. The 1:4000 scale airphotos were interpreted mainly because they were convenient to compare with other sets of airphotos (Fig. 3.8). The airphotos were taken at 17:15 on October 26. Since the airphotos were taken at a similar time to the 1987 airphotos the situation is almost the same. The scarp face of the East Slide, parts of the North Slide scarp, and some cracks in the graben in the North Slide are not visible. The extension of the East Slide is not clear. Some cracks were obscured by the trees and their shadows.

Figure 3.8 An overlay on the air photograph GRS-8991-Line1W-6 which was taken in 1989. (Scale 1:4000)

D
27

The minor scarp, at (-7.70, 4.30) in 3-C, became larger and higher than that of 1987 airphotos and many cracks formed. In 5-C, cracks which were obvious in the 1987 airphotos are not so clear in the 1989 airphotos because of the trees and their shadows. Many more cracks and scarps have formed in 6-A and 6-C. In 9-A, new cracks, bulges, and toes have formed (Fig. 3.8). The North Slide has advanced continuously.

In 1-D, cracks have widened more than those of 1987 airphotos. In 2-A, Several cracks have formed below the South Slide scarp at (-10.60, -1.00). A graben has formed from the cracks at (-7.90, 0.70) in 2-D. The area has moved almost perpendicular to the direction of the South slide movement.

In 5-C, 5-D, and 8-B, the toe of the East Slide formed across the creek and overlapped the toe of the South Slide at (-3.29, 0.41).

3.2.8 1991 airphotos

Two different airphoto sets of original scale 1:2000 and 1:5000 were available. The 1:5000 scale airphotos were mainly interpreted for the same reasons as the 1989 airphotos (Fig. 3.9, a-b). The airphotos were taken at 14:45 on April 21. Shadows did not affect the airphoto interpretation because the sun angle was high.

Figure 3.9-A An overlay on the air photograph NW1491-13 which was taken in 1991. (Scale 1:4000)

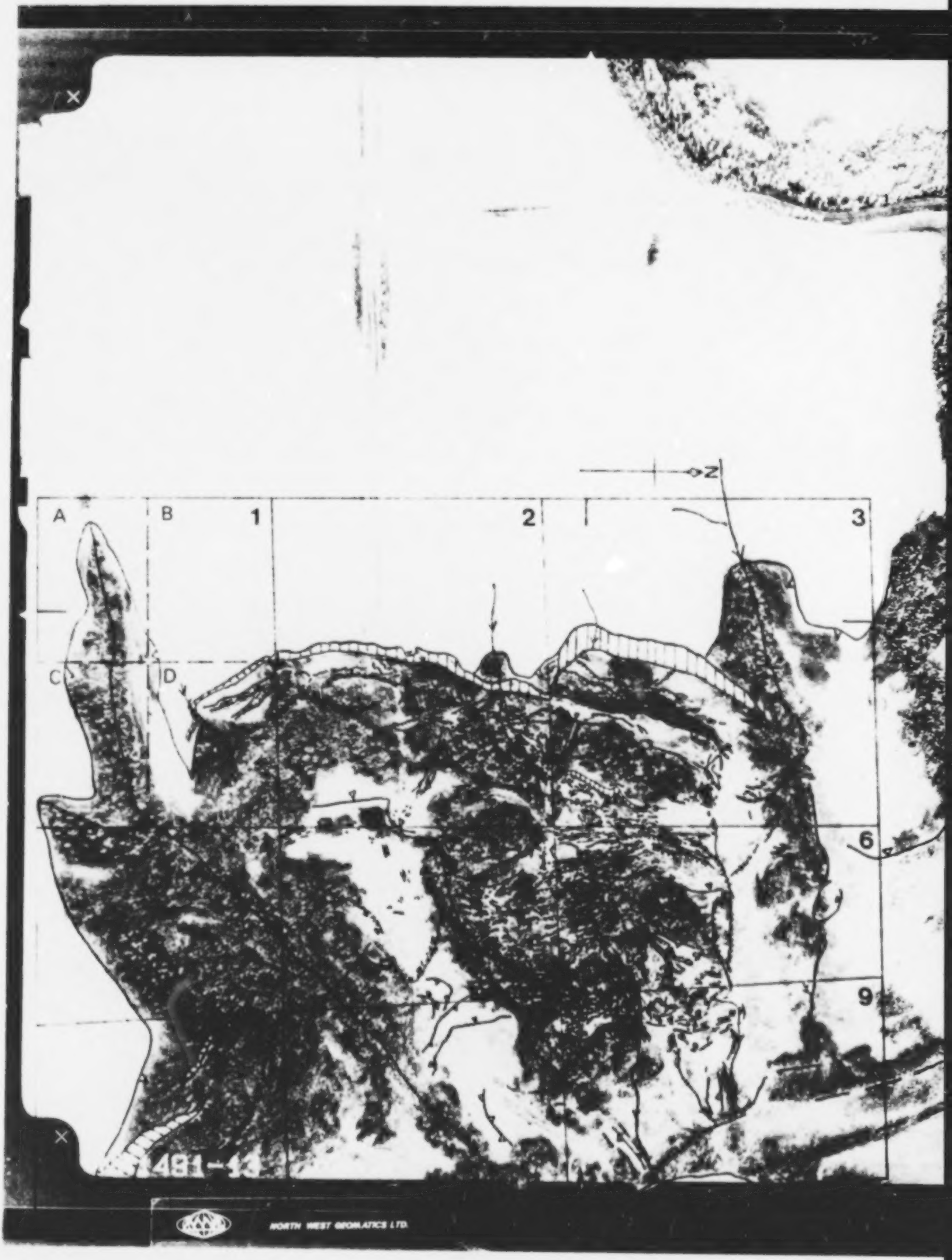

Z
A
B
1
2
3
C
D
6
9
481-13
NORTH WEST GEOMATICS LTD.

Figure 3.9-B An overlay on the air photograph NW1491-4 which was taken in 1991. (Scale 1:4000)

491-4
NORTH WEST GEOMATICS LTD.

along the creek near the north lateral margin of the North Slide, some cracks have formed parallel to the slope movement direction at (1.84, 4.12). In 5-B, 5-D, 6-A, and 6-C, the cracks and scarps are much more developed. In 9-A, cracks, scarps, and toes are more numerous and a pond has formed at (7.60, 2.30) (Fig. 3.9, a).

In 1-D, new cracks formed. In 2-A, many cracks were elongated and a new scarp formed in the block between the South Slide scarp and the antithetic scarp of the graben. Many more cracks developed in 2-D. In 5-C and 5-D, the toe of the South Slide is extended in both directions.

In 4-D and 5-C, new cracks have formed because of the East Slide movement (Fig. 3.9, a). The scale of the East Slide is obvious in the 1991 airphotos. In 7, 8, 10, and 11, the cracks and scarps developed much more because of the East Slide movement (Fig. 3.9, b). Cracks formed at (-1.75, 2.42) in 11-A, which is beyond the toe of the East Slide. Another crack is observed at (-3.10, 6.40) in 11-A but the crack may be caused by river activity.

3.3 Discussion

There is no remarkable change observed between the time of the 1949 and 1975 aerial photography, which could have affect the stability of the slope but some minor changes were noticed. Approximately 10 hectares of trees which existed about 650m behind the North Slide scarp in the 1949 airphotos were not present in the 1963 airphotos (Fig. 3.2). This area started to be used as farmland as mentioned the previous section. Studies by Gray (1970) showed that a forest cover could affect the deep-seated stability in two principal ways; viz., by modifying the hydrologic regime in the soil mantle and by mechanical reinforcement from its root system. Since forest area existed about 650m behind the North Slide scarp, only the first case could be considered as a possible factor for the instability of the study area. Trees transpire water through their leaves and this in turn depletes soil moisture. Therefore, forest clear-cutting in the area might decrease evaporation from the foliage and increase infiltration of surface water. The increase of infiltration due to forest clear-cutting may have contributed to the instability of the area.

Landslide topography was noticed in the study area from the observation of pre-landslide airphotos taken in 1949 and 1963. After the slope movement in 1974, the toe of the rupture surface of the North Slide, which is called the old toe, formed in 6-A (Fig. 3.4). The high slope angle of the old toe area had been there before the North Slide movement took place according to the 1963 airphotos. Also, the outline of the East Slide is close to the outline of old landslide topography in pre-landslide airphotos (Fig. 3.3). Therefore, the Edgerton landslides must be reactivations of old landslides. The old landslides of the area can be called dormant because the slope movements were reactivated (Varnes, 1978, p.26).

The slope movements of the area started from the scarp to the toe. Fig. 3.10 clearly shows the progress of the landslides in the study area. In 3-A, surface water flowed directly into the present North Slide scarp in 1963 airphotos (Fig. 3.3). Rib and Liang(1978, p.39) stated that seepage with subsequent sliding is likely to occur in areas below ponded depressions, reservoirs, irrigation canals, and diverted surface channels. Since the bedrock at the top of the North Slide was highly weathered and brecciated down to about 10m according to Tweedie(1976, p.23), the surface water which flowed into the slope might reduce the strength of the materials. This may be one possible factor in forming a tension crack at the present North Slide scarp.

A minor scarp of the North Slide formed in 3-C, which may be caused by the uplift of the area due to the North Slide movement (Fig. 3.6). The slope has been disturbed greatly in 5-B, 5-D, 6-A, 6-C, and 9-A (Fig. 3.9, a). The material which is involved in this slope movement is mainly colluvium of dormant landslides. After the slope movement started in 5-B

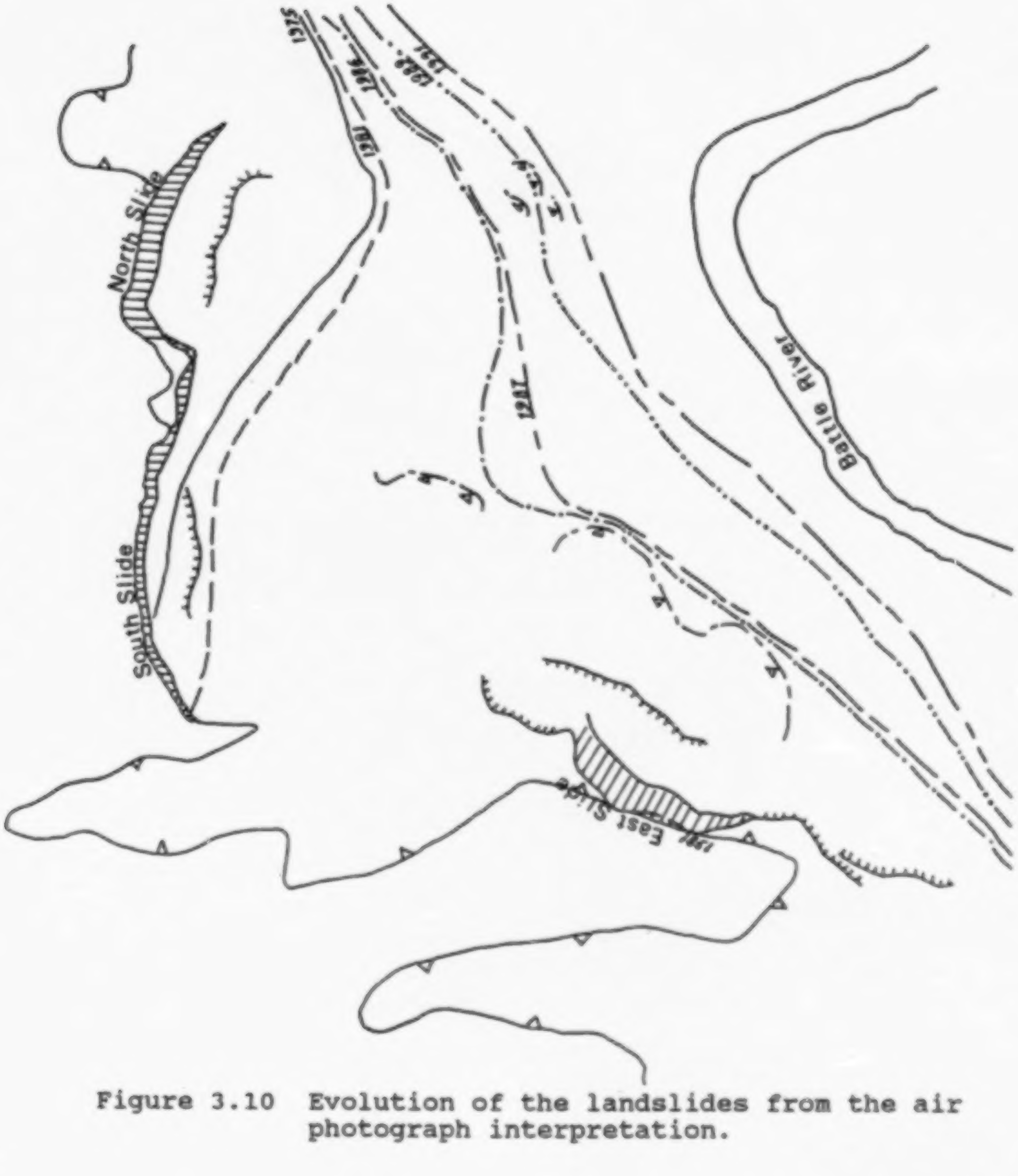

1975
North Slide
South Slide
East Slide
Battle River

Figure 3.10 Evolution of the landslides from the air photograph interpretation.

and 6-A the vegetation of the downslope area reduced, which may have resulted from the infiltration of surface water into the cracks. The surface water entering cracks and the disturbance of the area due to the North Slide movement may be the main factors to cause the slope movement in the area.

Many scarps and tension cracks have formed in 2-D (Fig. 3.9, a). The slope movement in this area indicates that the South Slide is still very active and the disrupted material moves horizontally.

The toe of the South Slide was not exposed in 1981 airphotos (Fig. 3.5) even though the height of the scarp was about 4.0m in June, 1981 (Mokracki, 1982, p.16). The lack of toe development resulted in uplift movement in 5-A shown by the survey results (Chapter 5). Many tension cracks have formed in the area and they show a linear arrangement (Fig. 3.9, a). These cracks may develop as a scarp in the near future like a minor scarp of the North Slide in 3-C because of the infiltration of surface water and disturbance of the materials due to the South Slide movement.

Some cracks have formed in 11-A and 11-B, which is outside the toe of the East Slide (Fig. 3.9, b). The cracks in 11-A may be related to the East Slide movement even though the cracks in 11-B may not. This observation suggests the toe of the East Slide is advancing, a suggestion confirmed by the ground surveying results (Appendix 2). In 11-A, a sudden change of slope angle, which may be related to the old landslides topography shows at (-2.00, 3.50) in the 1991 air photographs (Fig. 3.9, b). This area should be observed to check its relationship with the East Slide.

The directions of the slope movements in three landslides are different and the landslides overlap one another in 1991 airphotos (Fig. 3.9, a). Since the bedrock of the study area dips gently to the southwest, the rupture surfaces of the landslides do not follow a single bedding plane. One common phenomenon of these slides is the formation of grabens. Therefore, the shape of the rupture surfaces of the three slides should be similar, compound (Chapter 5).

The South Slide gradually expanded southwards. By 1980 it may have impeded drainage down its south flank which may have affected the stability of the mass to the east. The toe of the East Slide formed across the creek and overlapped the toe of the South Slide (Fig. 3.8). Therefore, the South Slide may have affected the stability of the East Slide.

The slope movements of the slides follow the rupture surfaces of dormant landslides according to the interpretation of air photographs. Since the landslides are reactivated, the area should be examined continuously. The South Slide and East Slide are expected to advance in the future like the North Slide movement.

Chapter 4

Analysis of Field Observation

4.1 General

Detailed field mapping was done from June 26 - July 5, July 17 - August 5, and August 28 - August 31, 1990 for about 5 weeks. Five airphotos (scale 1:2000), which were taken in 1987 and two airphotos (scale 1:2000) taken in 1989 were used to do field mapping with overlays. Figure 4.1 shows the positions of these airphotos in the study area. The results of the field mapping were drawn using symbols. Since the field mapping was done during the summer, many features were obscured by trees and grass.

The locations of observations are given by airphotograph number and co-ordinates as described in chapter 3. The reader can measure distance from the centre point using a grid overlay or a ruler to determine the position of the feature which is explained.

Many cracks, bulges, and other minor topographic details could be identified through field observation, which could not be noticed from the airphoto interpretation. The observed ground features were directly measured using tape and Brunton compass and compared with the airphotographs to see the development of those features.

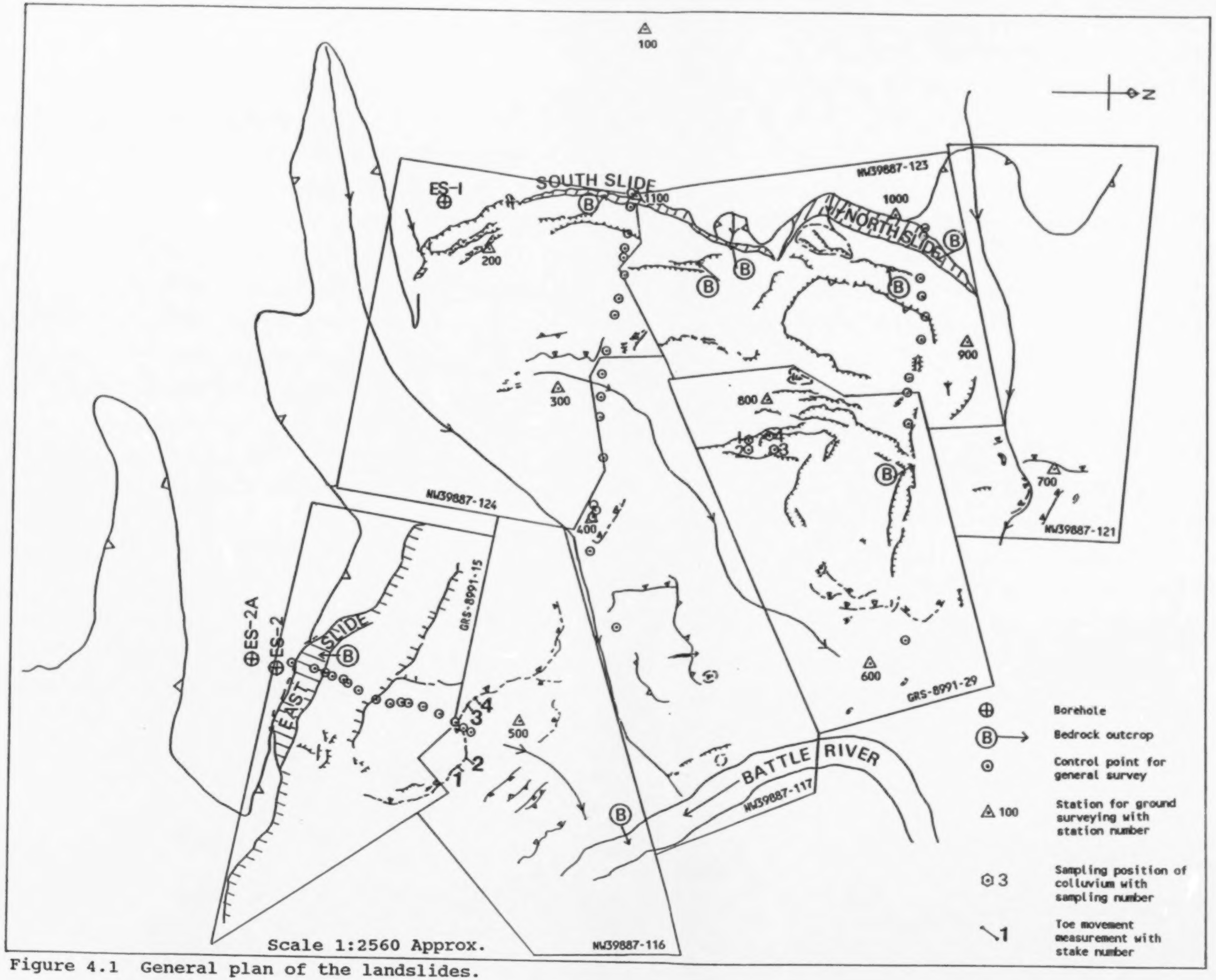

100
Z
SOUTH SLIDE
ES-1
NW39887-123
1000
1100
NORTH SLIDE
200
900
300
800
700
NW39887-124
NW39887-121
400
GRS-8991-15
ES-2A
ES-2
EAST SLIDE
500
600
GRS-8991-29
BATTLE RIVER
NW39887-117
NW39887-116
Scale 1:2560 Approx.
Borehole
Bedrock outcrop
Control point for general survey
100
Station for ground surveying with station number
3
Sampling position of colluvium with sampling number
1
Toe movement measurement with stake number

Figure 4.1 General plan of the landslides.

Although the North Slide and the South Slide occurred at different times, they merge together in the field. Therefore, it is difficult to say which ground feature is related to which slide movement. For this reason, this section is divided into two parts, i.e., the North and South Slides and the East Slide.

4.2 North and South Slides

Generally, the scarp of the North Slide is covered by vegetation and the landslide is inactive but the scarp of the South Slide is still active. Till, exhibiting columnar joints, is visible in the scarp face. The average thickness of the till is about 5m. Till is underlain by the brecciated and weathered clay shale, which is interbedded with sandstone.

Several gullies developed along the scarp. The cross sections of these gullies are U-shaped, which are usually formed in silty soils. The gully, at (-0.90, 4.65), lacks vegetation on the wall, U-shaped, and connected to the bottom of the scarps in airphotograph NW39887-123 (Fig. 4.2). At (1.70, 9.15), many trees have fallen and there is no vegetation along the scarp. The scarp may be retreating continuously by weathering processes.

A tension crack which is parallel to the scarp is observed behind the South scarp at (0.65, 1.14). The length of

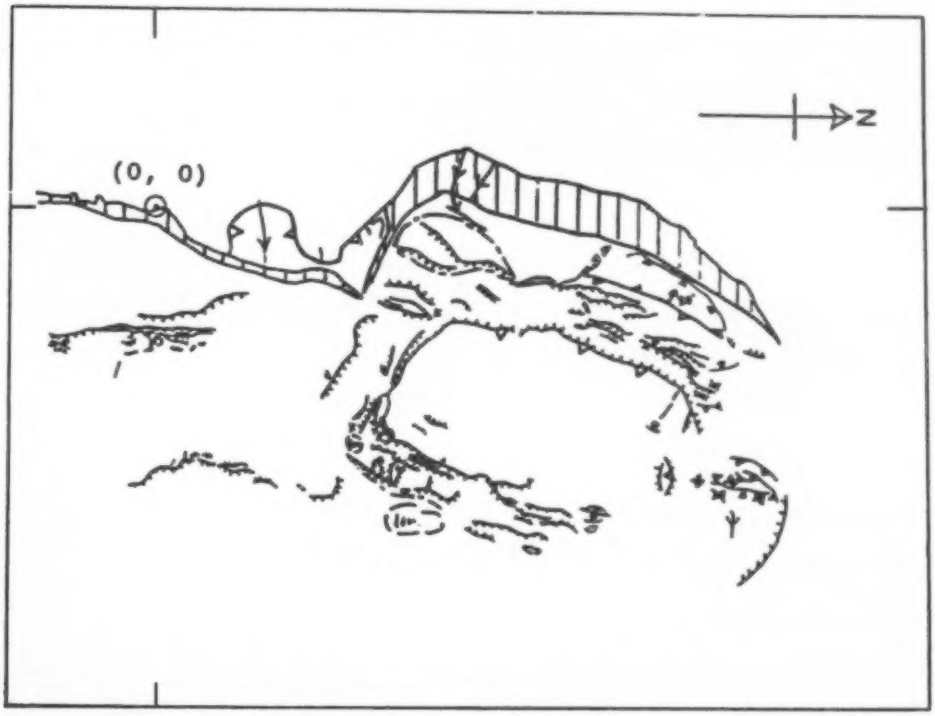


Figure 4.2 A geomorphological map on the air photograph NW39887-123 which was taken in 1987.

the crack is 1m and width is 5cm. The crack could not be traced further because of trees. This crack may have contributed to the retreating of the scarp.

The boundary between the North and South Slides is at (1.38, 3.09). The boundary of these scarps is not clear because of thick vegetation but they are almost merging.

The scarp, at (-0.16, 4.58), is one of the most active parts of the South Slide scarp in airphotograph NW39887-124 (Fig. 4.3). The scarp has retreated more compared to the 1987 airphotos and lots of talus are deposited at the bottom of the scarp.

A garbage tip was found at the South scarp at (0.02, 4.10). The garbage tip is covered by clays and is about 0.3m thick. A drainage channel formed at (0.6, 3.74). When this area was revisited in 1991 the drainage channel was much disturbed due to the movement of displaced material.

At the southern part of the South Slide, a graben formed (Fig. 4.4). The height of the scarp cannot reliably be measured because of talus. The scarp is almost vertical and many till blocks are still standing even though separated from the main scarp. These blocks may fall down as a toppling failure someday. The slope movement in this area, from the

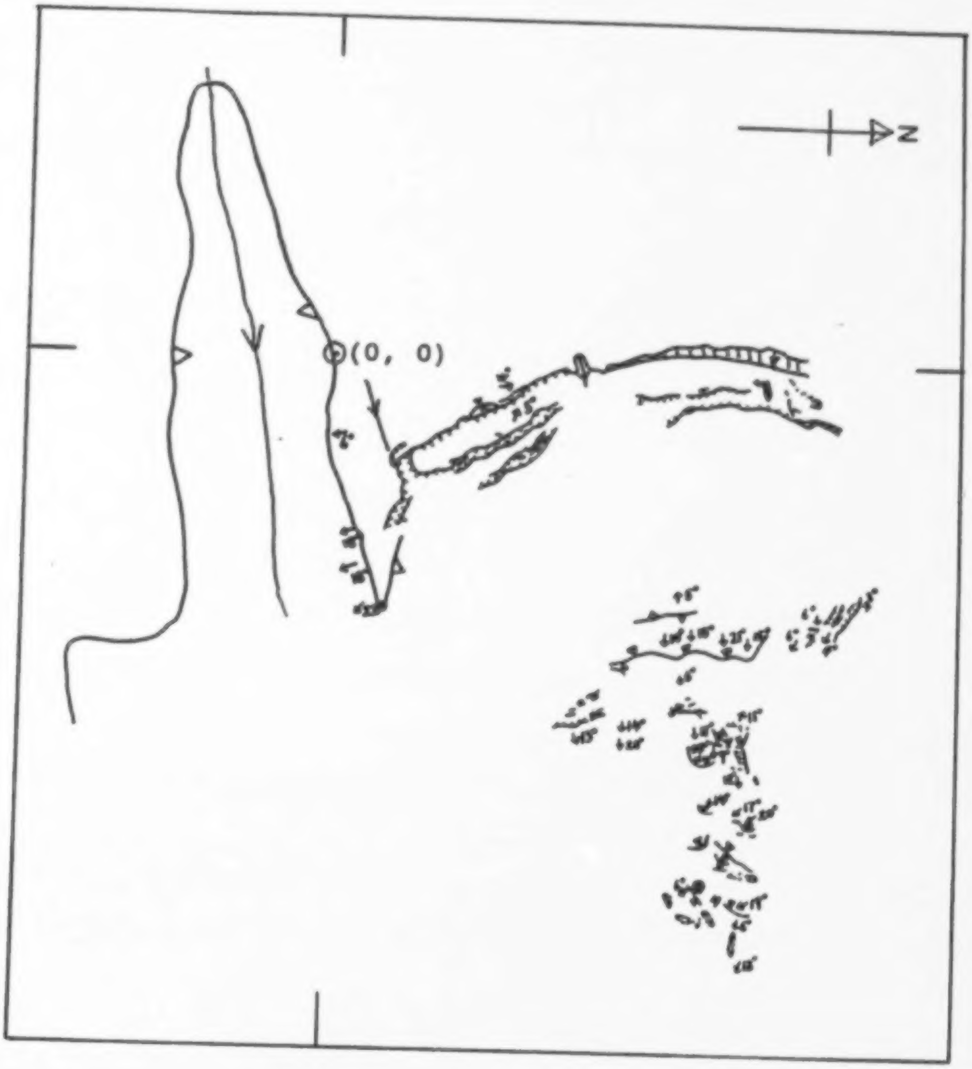


Figure 4.3 A geomorphological map on the air photograph NW39887-124 which was taken in 1987.

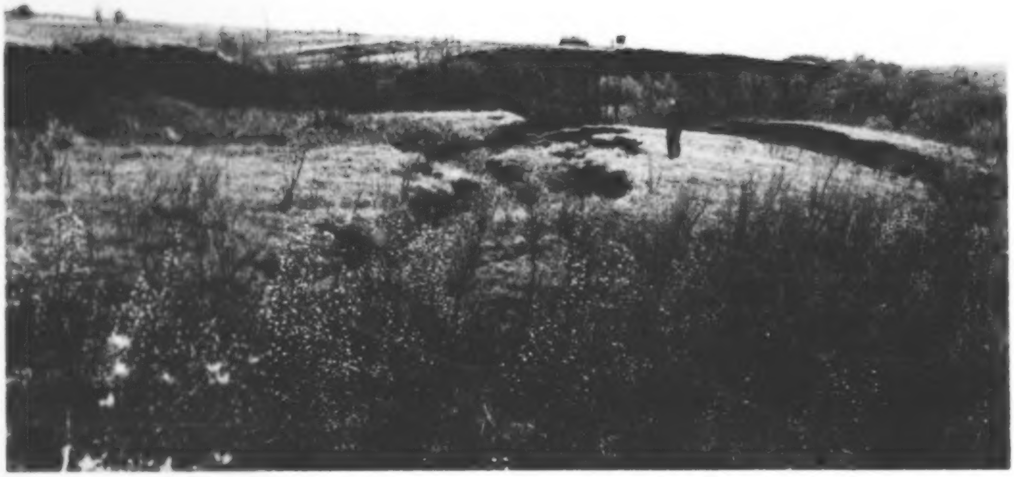


Figure 4.4 General view of the scarp and graben of the South Slide. (May, 1991)

formation of a graben, almost vertical scarp, and no sign of rotational movement, should be translational or compound.

A drainage channel formed at (1.00, 0.65). The drainage channel is identified by the depression of the ground. The south end of the South Slide, at (2.30, 0.89), is a very active area. The area is more developed compared to the 1987 airphotos. Many blocks had fallen down at the bottom of the scarp. The scarp is about 1.7m high and 1.5m wide. When this area was revisited in 1991, the South scarp was extended more to the south.

The left flank of the North Slide is found at (5.00, 9.13) in airphotograph NW39887-123 (Fig. 4.2). The flank is about 34m long and about 1m high.

A graben has formed at the North Slide area (Fig. 4.5). Several small scarps formed between the North Slide and antithetic scarps. Bedrock, interbedded sandstone and clay shale, is exposed along the scarp at (1.20, 6.60). The bedrock is about 0.3m thick, completely weathered, and overlain by till.

The slope angle, downslope of the antithetic scarp, is about 21°, which is steeper than regional slope angle, 11°. This high slope angle may be caused by the uplift movement of

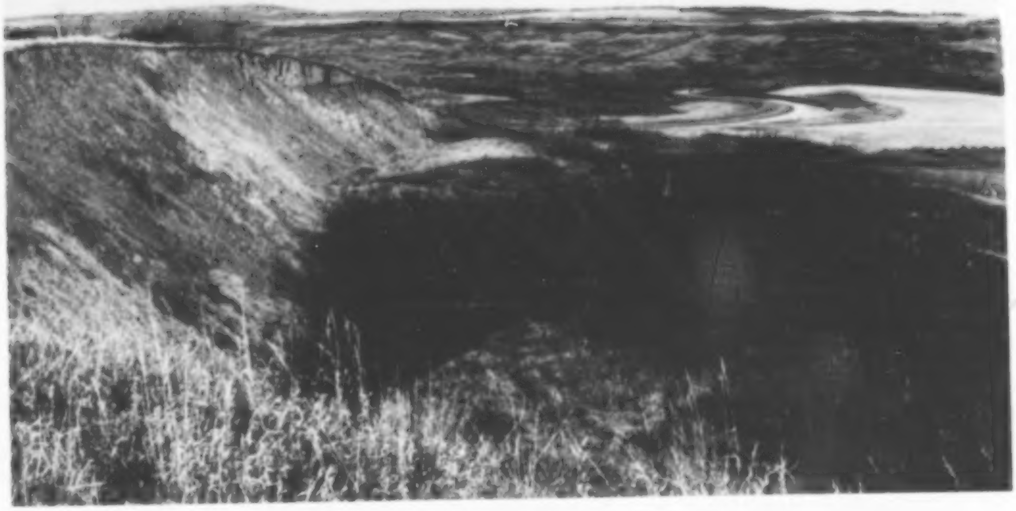


Figure 4.5 General view of the scarp and graben of the North Slide. (April, 1992)

the area due to the poor development of the toe of the North Slide at the time of the North Slide movement.

A minor scarp formed downslope of the North Slide at (4.00, 4.50) (Fig. 4.6). This slope movement is an advancing failure of the North Slide. The scarp is about 4.5m high and bedrock which is composed of clay shale is exposed along the scarp.

Bedrock, interbedded clay shale and sandstone, is exposed along the left flank of the North Slide at (6.70, 7.70) (Fig. 4.7). The bedding plane dips gently to the west, possibly southwest, which is opposite to the direction of the North Slide movement.

Many scarps and cracks have formed in the lower bodies of the displaced material of the North and South Slides. The material which is involved in these slope movements is the colluvium of dormant landslides. The slope movements may be caused by uplift at the toes of the North and South Slides and accelerated by concentration of the surface water in the slide area. The colluvium material was sampled and tested (Chapter 6).

An old toe is observed at the slope across the creek from the North Slides to the north at (7.05, -3.90) in

Figure 4.6 General view of the scarps of the North, the South, and minor slides. (May, 1991)

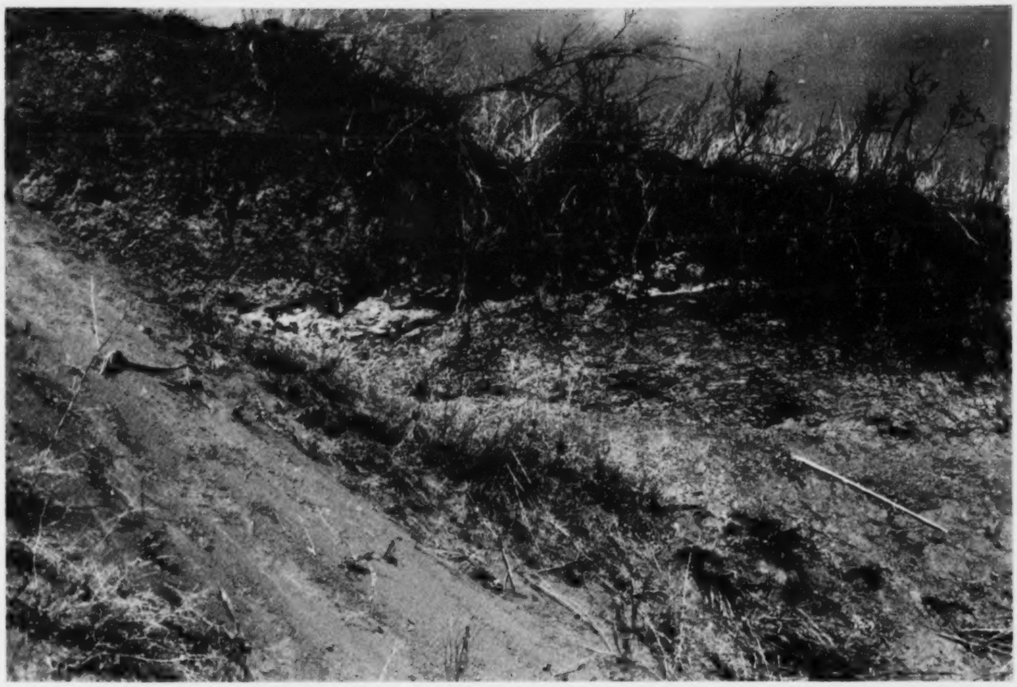


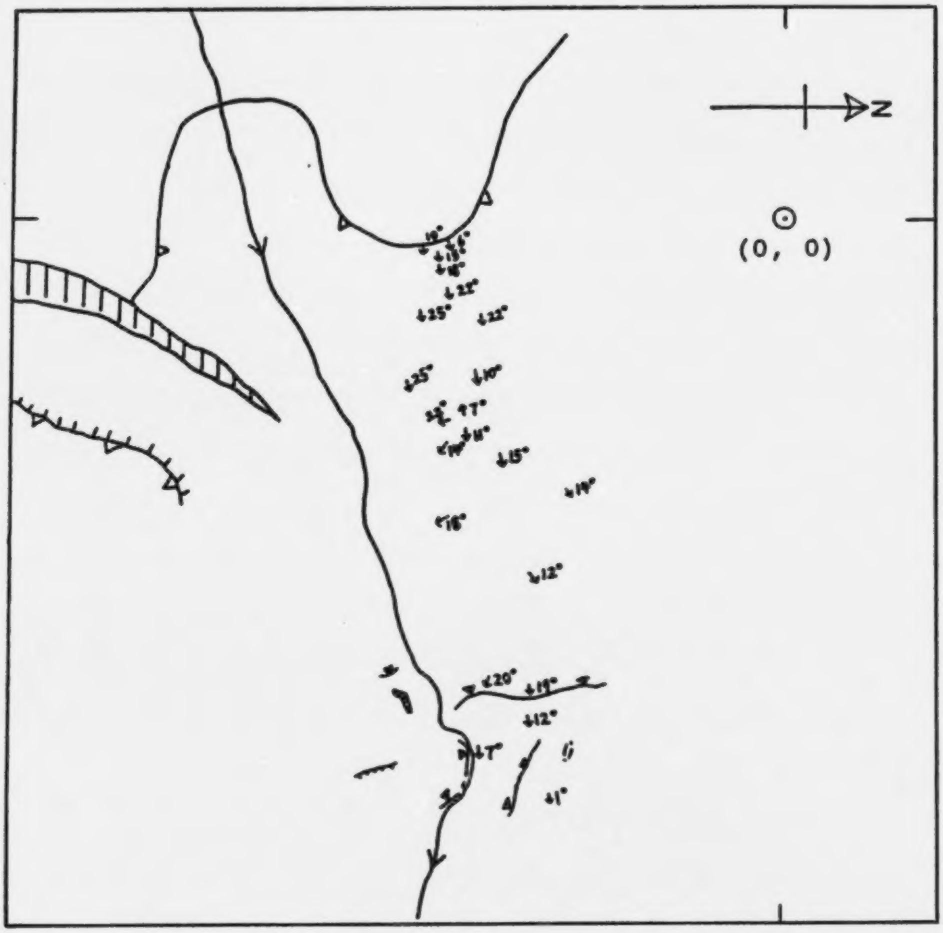
Figure 4.7 Bedrock exposure along the left flank of the North Slide, Scale of tape 1m. (April, 1992)

airphotograph NW39887-121 (Fig. 4.8).

A spring is found at (3.70, 6.50) in airphotograph GRS-8991-29 (Fig. 4.9). The elevation of this spring is roughly matched with that of the toe of the North Slide.

Figure 4.10 shows the toe of the North Slide. A bulging feature is observed far below of the toe of the North Slide at (8.00, 5.00). This feature may be related to the North Slide because movement was detected outside of the toe area, which is located near the bulging feature, from the ground surveying (Peterson, 1992) (Appendix 2). Therefore, the toe of the North Slide may be advancing.

A scarp has formed facing downhill below the South Slide at (1.58, 0.82) in airphotograph NW39887-123 (Fig. 4.2). Bedrock, which is composed of clayshale, is exposed in the scarp. Talus is deposited at the bottom of the scarp and the height of the scarp is about 1.10m. The scarp cannot be traced further to the north because of the trees. Some blocks were separated from the original position and moved downhill at (1.76, -0.50). Some blocks were separated horizontally more than 2m. A block was separated and another block was separated from the disrupted block, showing a step-like feature at (1.80, -0.10). A crack developed parallel to the slope movement at (2.41, -0.53). The crack is 0.5m wide and 1.50m


Z
(0, 0)
19°
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18°
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22°
25°
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7°
11°
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1°

Figure 4.8 A geomorphological map on the air photograph NW39887-121 which was taken in 1987.

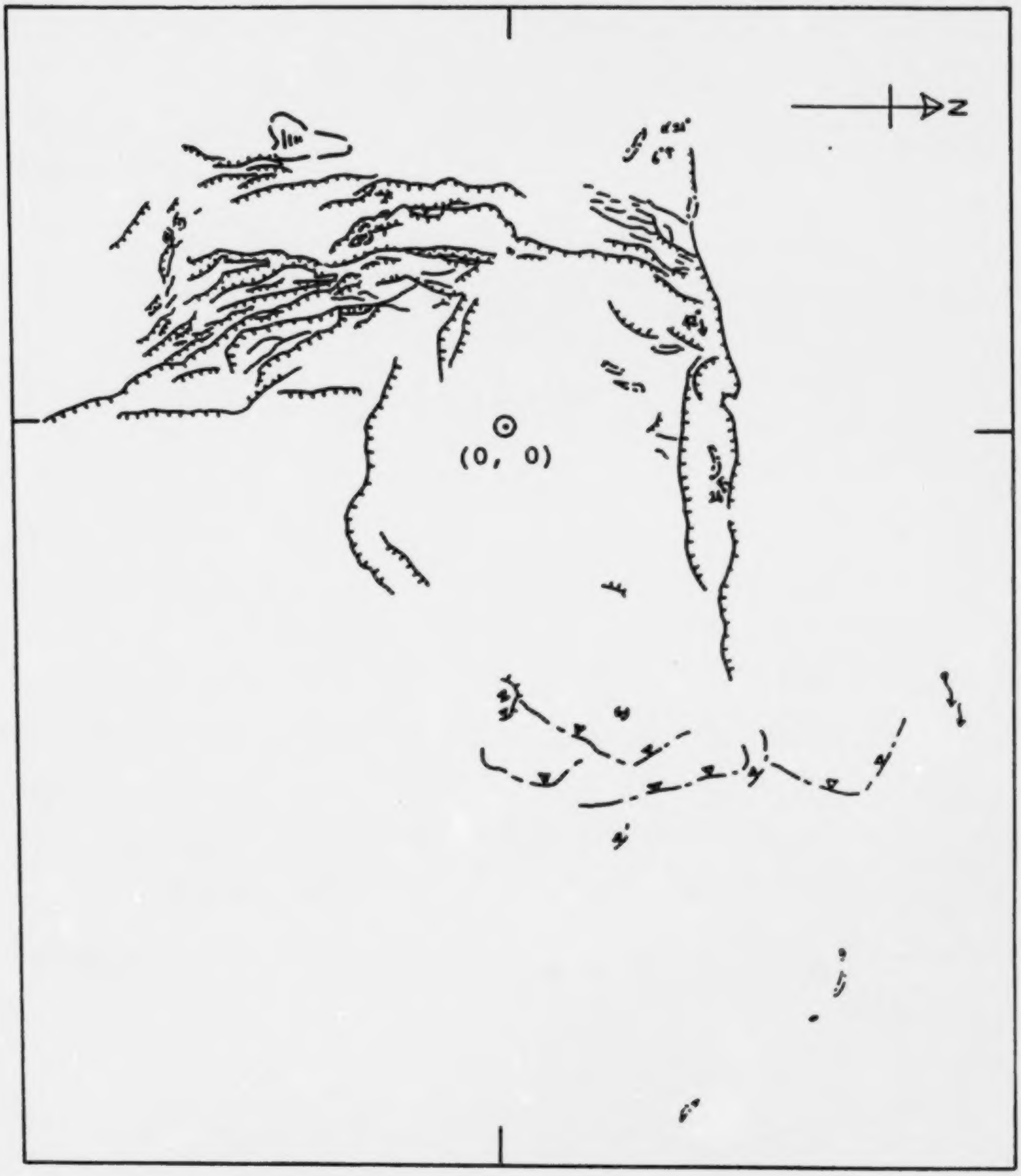


Figure 4.9 A geomorphological map on the air photograph GRS-8991-29 which was taken in 1989.

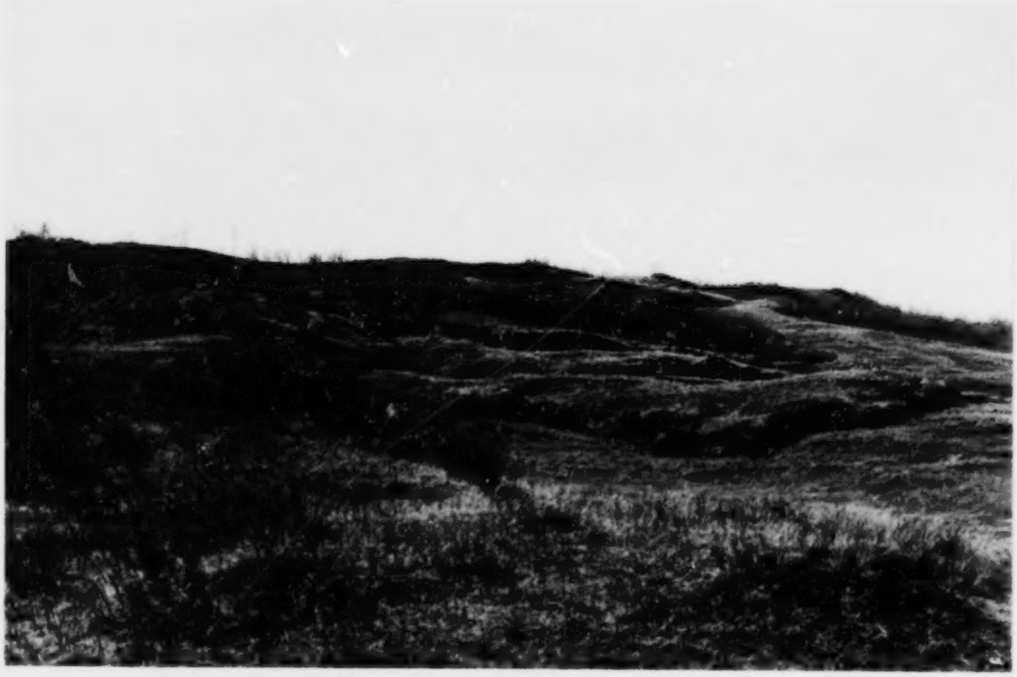


Figure 4.10 General view of the toe of the North Slide. (April, 1992)

deep.

A scarp has formed by horizontal and vertical movement at (4,30, 2.60). The horizontal and vertical movements are 1.14m and 0.45m respectively and the angle of the scarp is oversteepened. The scarp cannot be traced further to the north because of trees.

Several tension cracks have formed at (5.05, 5.35) in airphotograph NW39887-124 (Fig. 4.3). They are about 2m deep and 0.3m wide. These tension cracks are long, numerous, and show a linear arrangement in 1991 airphotographs. These cracks may develop as a scarp in the future (Chapter 3).

A scarp which is about 0.2m high is found near the Battle River at (8.80, 8.10) in airphotograph NW39887-117 (Fig. 4.11). This feature may not be related to the South Slide because there is no sign of slope movement between the toe of the South Slide and this feature.

4.3 East Slide

The East Slide scarp is about 18m high. Bedrock mainly composed of weathered clay shale is exposed in the scarp and is overlain by till at the top of scarp, which is about 4m thick. The average dip angle of the scarp is about 65° but the upper part of the scarp is sub-vertical. Several cracks have

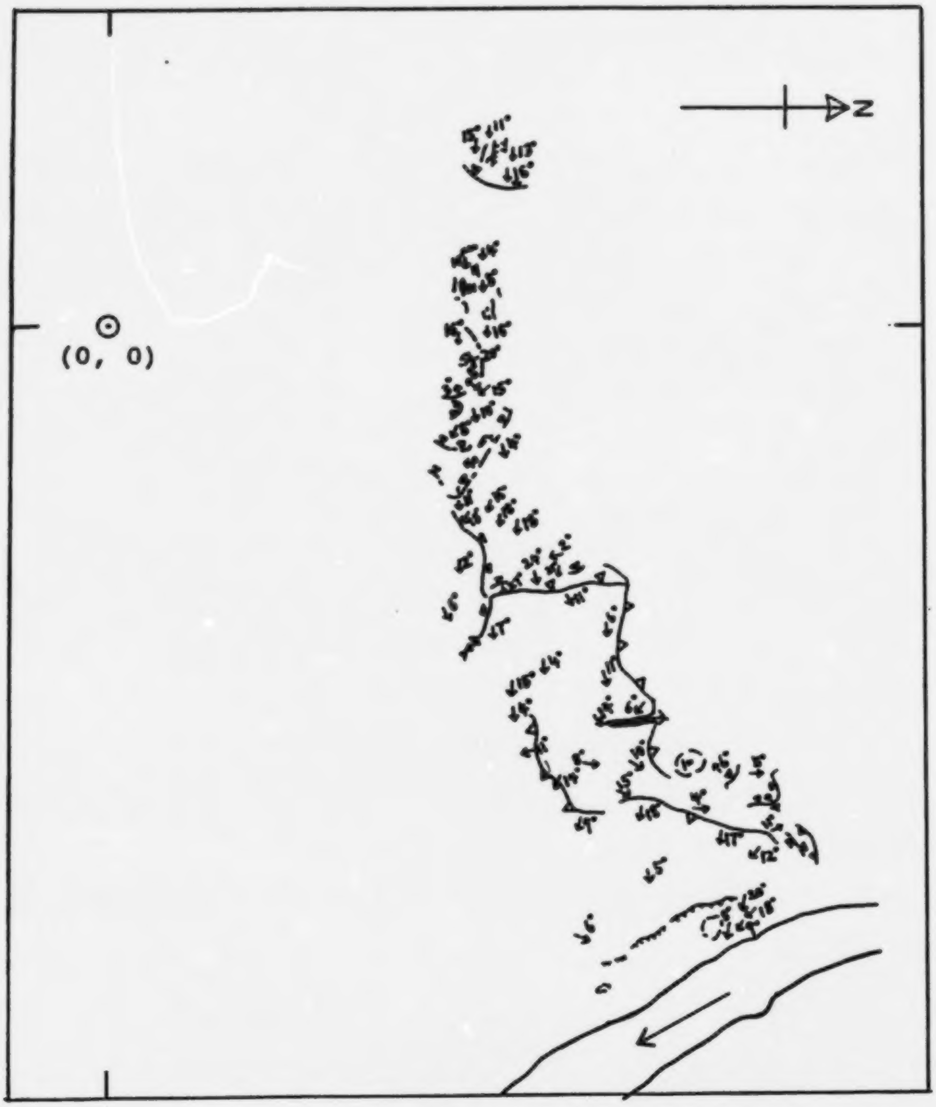


Figure 4.11 A geomorphological map on the air photograph NW39887-117 which was taken in 1987.

formed behind the scarp parallel to the scarp face. Those cracks may have contributed to the retreat of the scarp.

Downslope of the East Slide scarp, another scarp has formed facing uphill. The block between these two scarps has moved downward and a graben has formed. The uphill-facing scarp is about 3m high and dips at an angle of 53° at (-0.13, -4.00) in airphotograph GRS-8991-15 (Fig. 4.12).

Some trees are slightly tilted uphill in the graben area as a result of rotational movement of displaced material but the main parts of the rupture surface should be translational which is indicated by the formation of graben. Therefore, the shape of the rupture surface is estimated as compound.

The toe of the East Slide is easily recognized in the field. Many tension cracks have formed due to the lateral and uplift movement of the toe area (Fig. 4.13). Most of these tension cracks at the toe area developed perpendicular to the slope movement direction. A crack formed at (4.00, -2.68). The crack is 1.42m wide and 0.93m deep. Some cracks in the toe area developed as scarps due to the vertical movement of the disrupted blocks. The ground is depressed and wet at (-0.54, 2.90) in airphotograph NW39887-116 (Fig. 4.14). Cracks are more numerous and longer than shown on the 1987 airphotograph at (-0.20, 3.82).

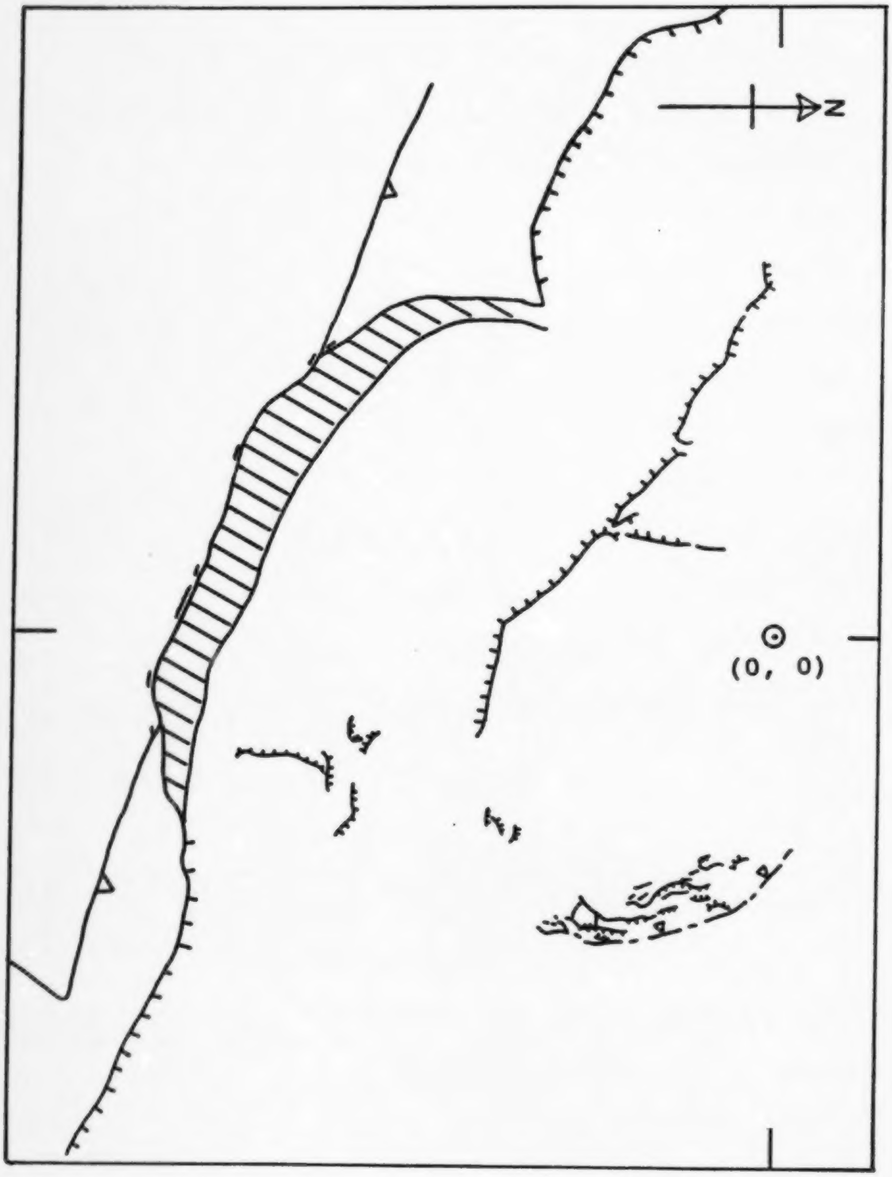


Figure 4.12 A geomorphological map on the air photograph GRS-8991-15 which was taken in 1989.

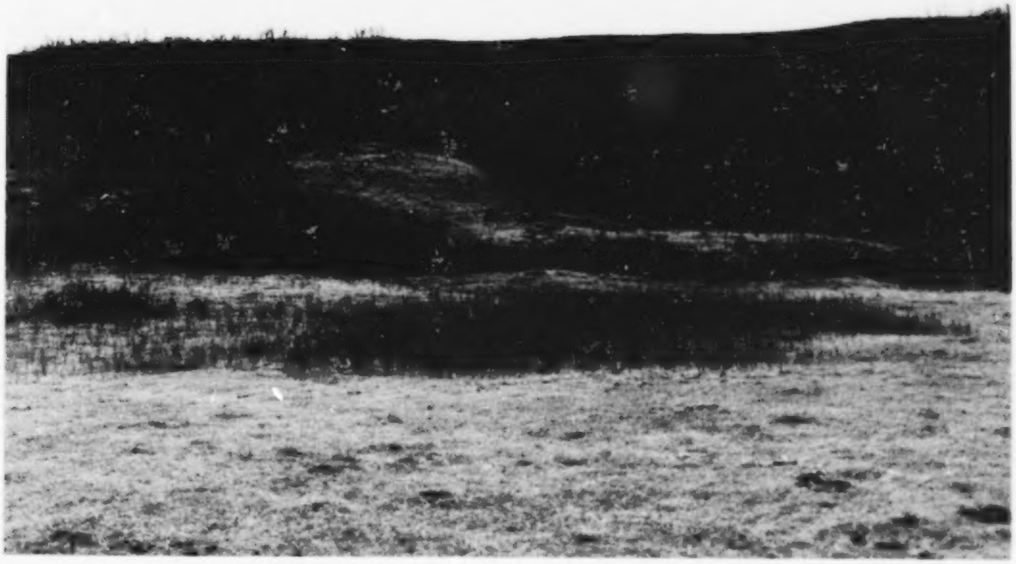


Figure 4.13 General view of the scarp and toe of the East Slide. (April, 1992)

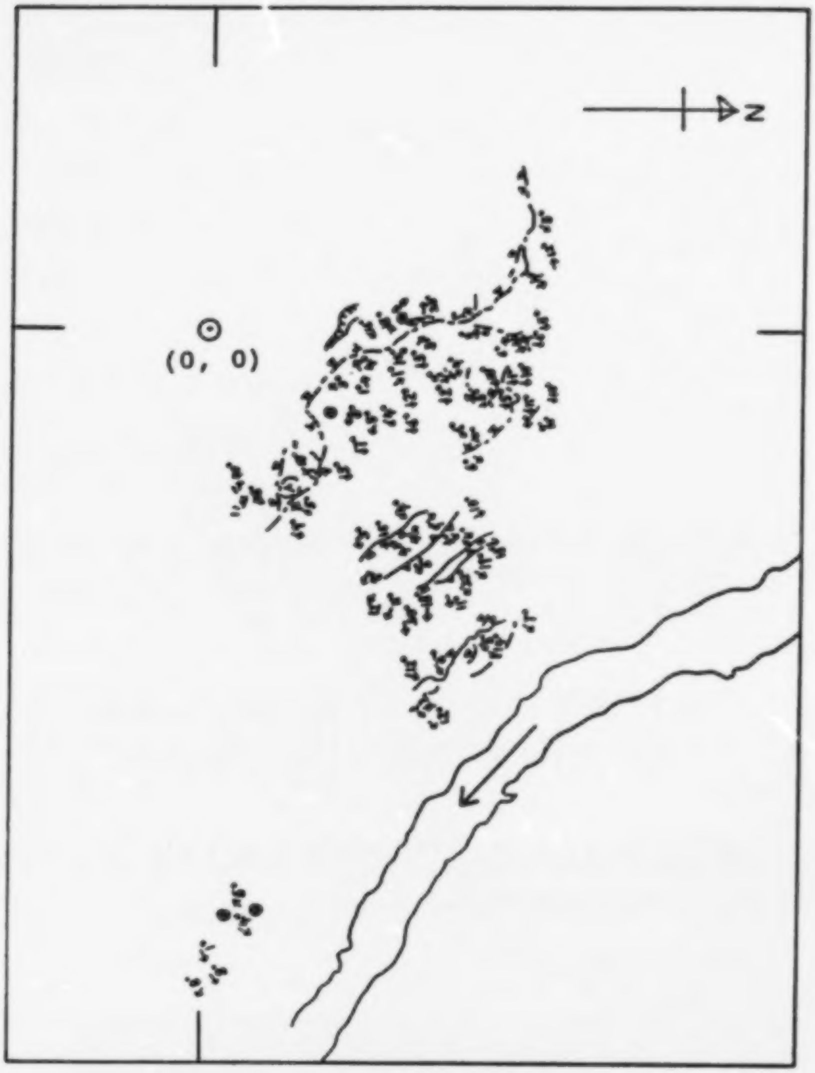


Figure 4.14 A geomorphological map on the air photograph NW39887-116 which was taken in 1987.

The toe of the East Slide is active as indicated by tilted grass along the toe at (2.60, 1.30). In order to detect the movement of the toe, 4 stakes were driven into the stable ground and 4 points were marked using white paint at the toe. The exact position of the stakes and the paint marks are located on Fig. 4.1. The distances from the stakes to the paint marks were measured using a tape and the results are shown in Table 4.1. Actually, the measurements of displacement are minimum values of the toe movement because the tip of the landslide may be different from the position of the paint marks. According to the results, there were a little movement of the toe during the summer in 1990. When the landslide area was revisited in 1991, the movement was obvious. The toe had moved about 0.5m over the last year. The toe had moved about 0.4m when the area was revisited in April, 1992. From the observation of the toe movement, the possibility of the movement of the toe may be the highest during early spring, which is well supported by the stability analysis of the area (Chapter 7). Some trees had fallen down at (1.23, 1.32) because of the toe movement.

Bulges formed in front of the toe at (2.63, 1.26) and some cracks formed on top of the bulges. Furthermore, station 500 which is located beyond the toe of the East Slide had moved about 0.18m from 1990 to 1991 according to the ground surveying results (Appendix 2). From these observations, the

Table 4.1 Measurements of toe movement in the East Slide (M).

	JK 1	JK 2	JK 3	JK 4
June 29, 1990	9.58	8.26	7.02	6.63
July 3, 1990	9.58	8.26	7.02	6.63
July 17, 1990	9.58	8.25	6.97	6.59
July 21, 1990	9.58	8.25	6.97	6.59
July 30, 1990	9.58	8.25	6.97	6.59
Aug. 31, 1990	9.51	8.25	6.93	6.57
Aug. 5, 1991	9.22	7.71	6.26	5.88
Apr. 17, 1992	8.68	7.44	5.93	5.56

toe of the East Slide advanced more but the location of the toe is not certain at the moment. Between the toe of the East Slide and Battle River, at (5.02, 3.52), some bulging features and breaks of slope are observed, which may be related to dormant landslides. Therefore, this area should be examined continuously to detect the actual toe of the East Slide.

Chapter 5

Site Investigation

5.1 General Survey

From the time that major slope movement was first observed in 1974, the landslides have been studied by personnel from the Department of Civil Engineering, University of Alberta.

Two survey lines were established down the South Slide, one at the midpoint of the scarp and the second at the south end of the scarp (Tweedie, 1976, p.35). Only the first survey line at the midpoint of the South Slide has been surveyed continuously.

In June, 1981, one survey line was placed down the East Slide (Mokracki, 1982, p.45). Another survey line was established down the North Slide in 1987.

To study the surface movements of the slide area, a series of control points were established through the survey lines. The area has been surveyed periodically. These survey lines were used to get the profile of the landslides and to determine the ground surface movement associated with landslides in this study. The locations of the survey lines are shown in Fig. 4.1.

In the field, the relative horizontal distance and relative vertical elevations of the control points were observed by either levelling to provide the vertical elevations of the control points followed by chaining or stadia surveying or through the use of an electronic distance measuring(E.D.M.) instrument to establish the relative horizontal distances between control points (Mokracki, 1982, p.20). The results of surveying are not very satisfactory for the following reasons. First, movement vectors can be obtained for a few points for the South and the East Slides because many control points were missing and new control points were used. Second, there were no stable control point outside of Slide masses in case of the North and the East Slides. Third, the number of control points for the North Slide slope was not enough to get an accurate profile. However, information can be obtained from the surveying results combined with the airphoto interpretation and field observation, which is presented in the following section.

The movement of the area has been monitored by ground surveying using an E.D.M. instrument from 1990 and the results are shown in Appendix 2 (Peterson, 1992).

5.2 Profile of landslides

5.2.1 North Slide

The original survey line of the North Slide in 1987 was changed in 1990 because the original hubs in the top of the scarp were lost due to cultivation of the area and the position of the control points in 1991 is different from those of 1990. Therefore, these profiles are not directly comparable but vertical uplift is noticeable near the new toe area (Fig. 5.1) which agrees well with airphoto interpretation and field observation (Chapter 3 and 4).

The profile of the North Slide was drawn from survey results and airphotographs in 1991 (Fig. 5.2). After the slope movement in 1974, the toe of the rupture surface of the North Slide, which is called the old toe, formed about 180m horizontally from the scarp. The high slope angle of the old toe area had been there before the North Slide movement took place according to the interpretation of the pre-landslide airphotographs (Chapter 3). From this observation, the North Slide must be a reactivation of an dormant landslide.

The rupture surface of the North Slide was estimated based on the profile of the North Slide and Tweedie's(1976) slope indicator study (Fig. 5.2).

5.2.2 South Slide

The original ground profile of the South Slide in 1975 and two other profiles in 1986, and 1991 are shown in Fig.

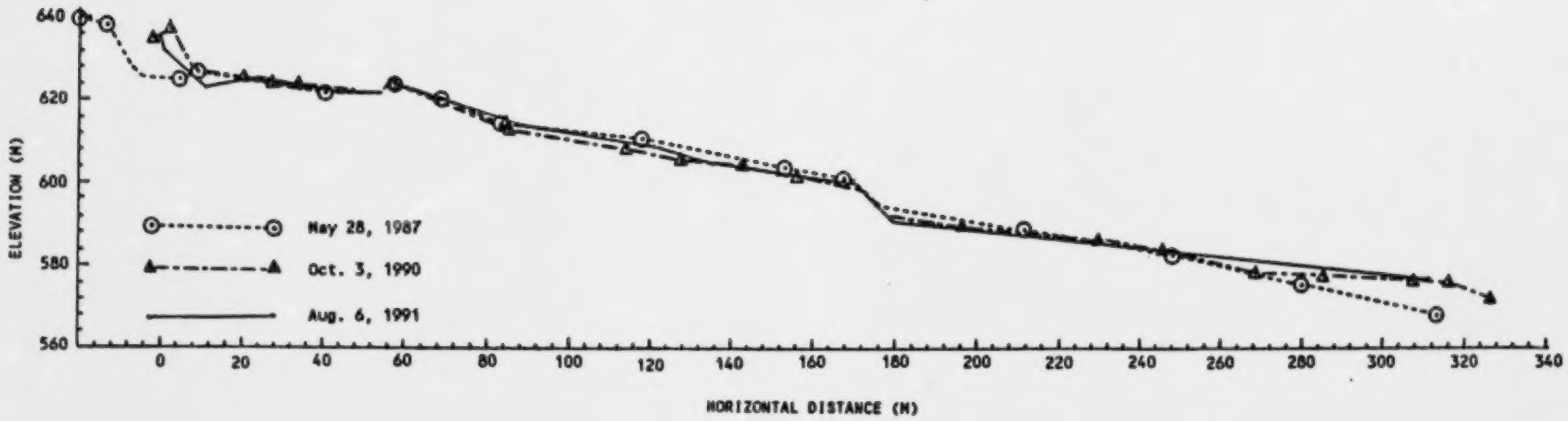


Figure 5.1 Change of profile of the North Slide.

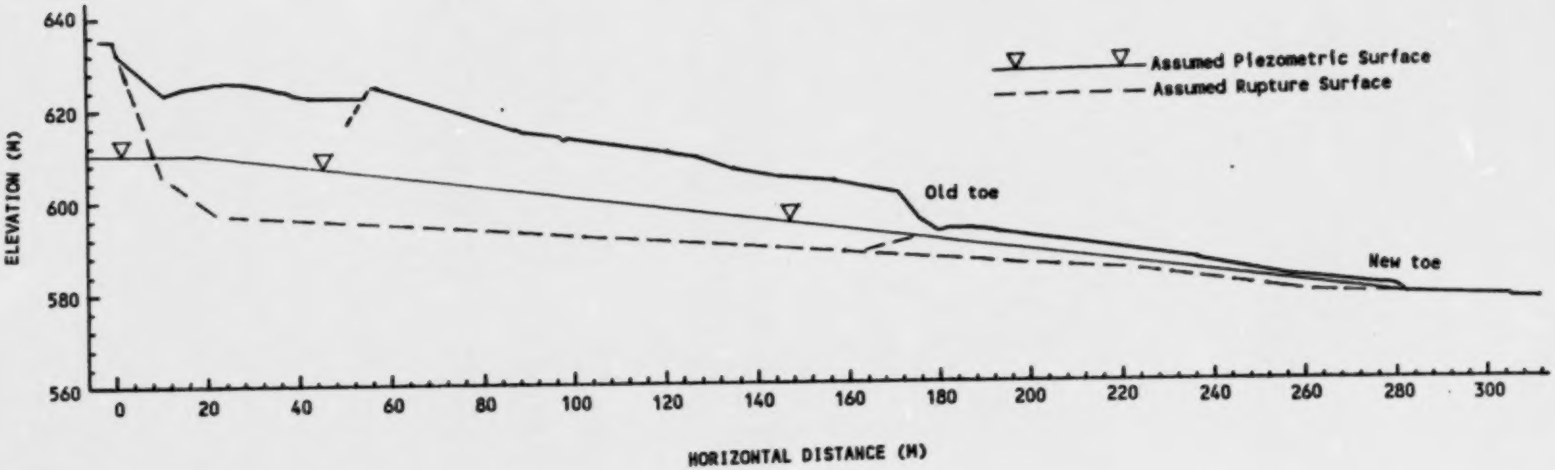


Figure 5.2 Profile of the North Slide.

5.3. The most recent profile of the South Slide was drawn from the survey results and airphotographs of 1991 (Fig. 5.4).

The movement vectors from 1975 to 1981 and from 1986 to 1991 are drawn using arrows with letters and arrows with numbers respectively in Fig. 5.4. The rupture surface was drawn from the Tweedie's(1976) slope indicator study and the change of slope profile.

The toe of the South Slide was not exposed in 1981 which resulted in the uplift movement vectors in the region A (Fig. 5.4). The elevation of the region lowered in 1986 profile as the toe of the South Slide developed and became visible.

Another toe was exposed far below the toe of the South Slide. This toe is related to the East Slide according to the airphoto interpretation (Chapter 3).

5.2.3 East Slide

The original ground profile of the East Slide in 1981 and two other profiles in 1987 and 1991 are shown in Fig. 5.5. The control points of each profile cannot be compared with those of other profiles accurately because many control points were missing and new control points were used for new profiles. In spite of this problem, the profiles clearly show the development of the East Slide. The scarp of the slide had

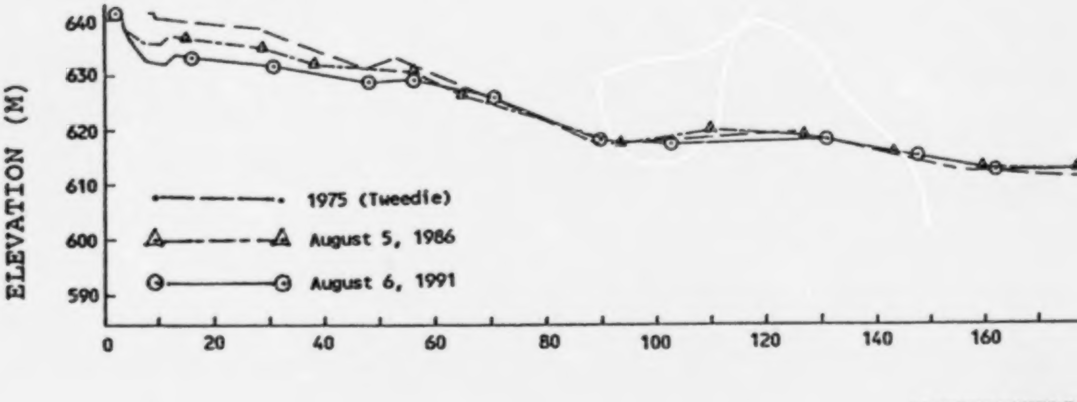
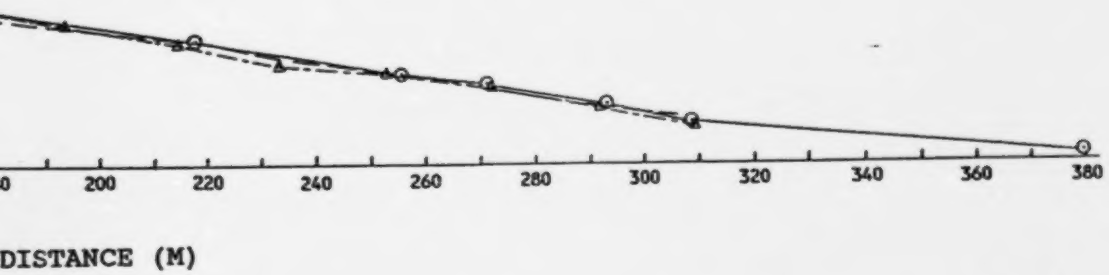


Figure 5.3 Change of profile of the South Slide.


0
200
220
240
260
280
300
320
340
360
380
DISTANCE (M)

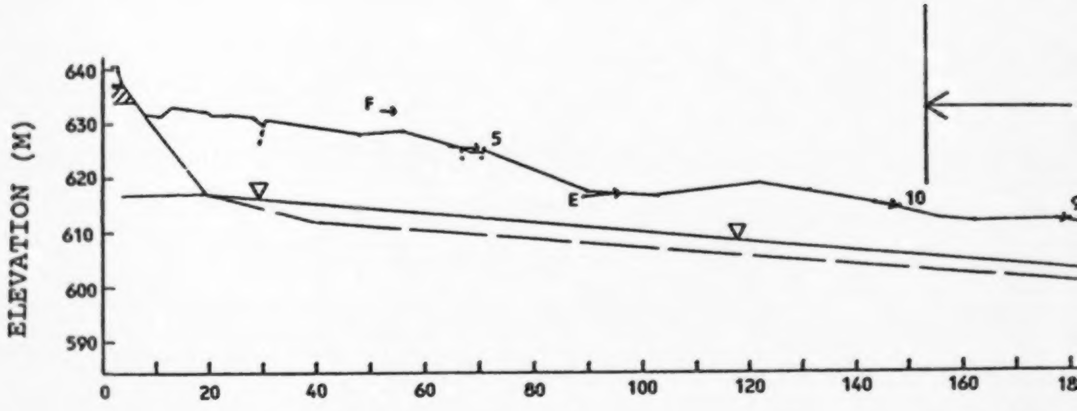
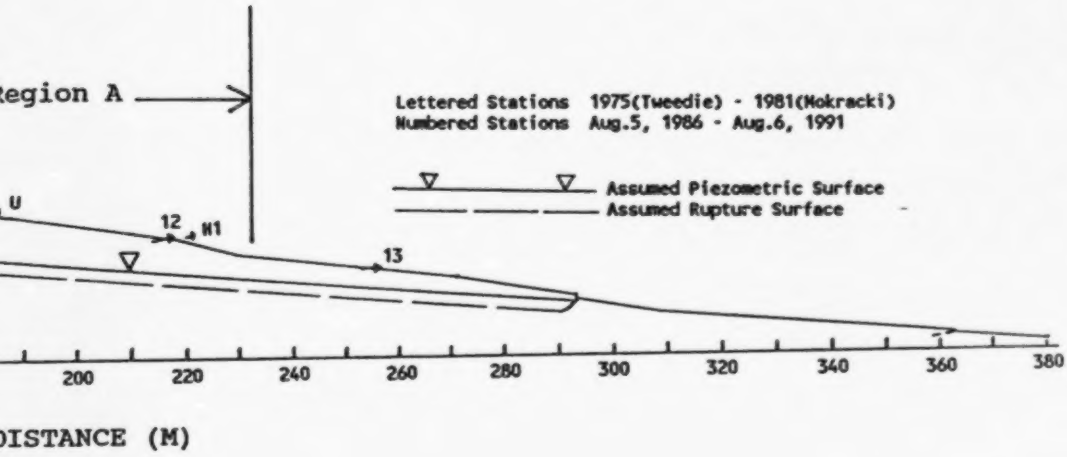


Figure 5.4 Profile of the South Slide and associated mov


Region A
Lettered Stations 1975(Tweedie) - 1981(Mokracki)
Numbered Stations Aug.5, 1986 - Aug.6, 1991
Assumed Piezometric Surface
Assumed Rupture Surface
U
12
H1
13
200
220
240
260
280
300
320
340
360
380
DISTANCE (M)

ement vectors.

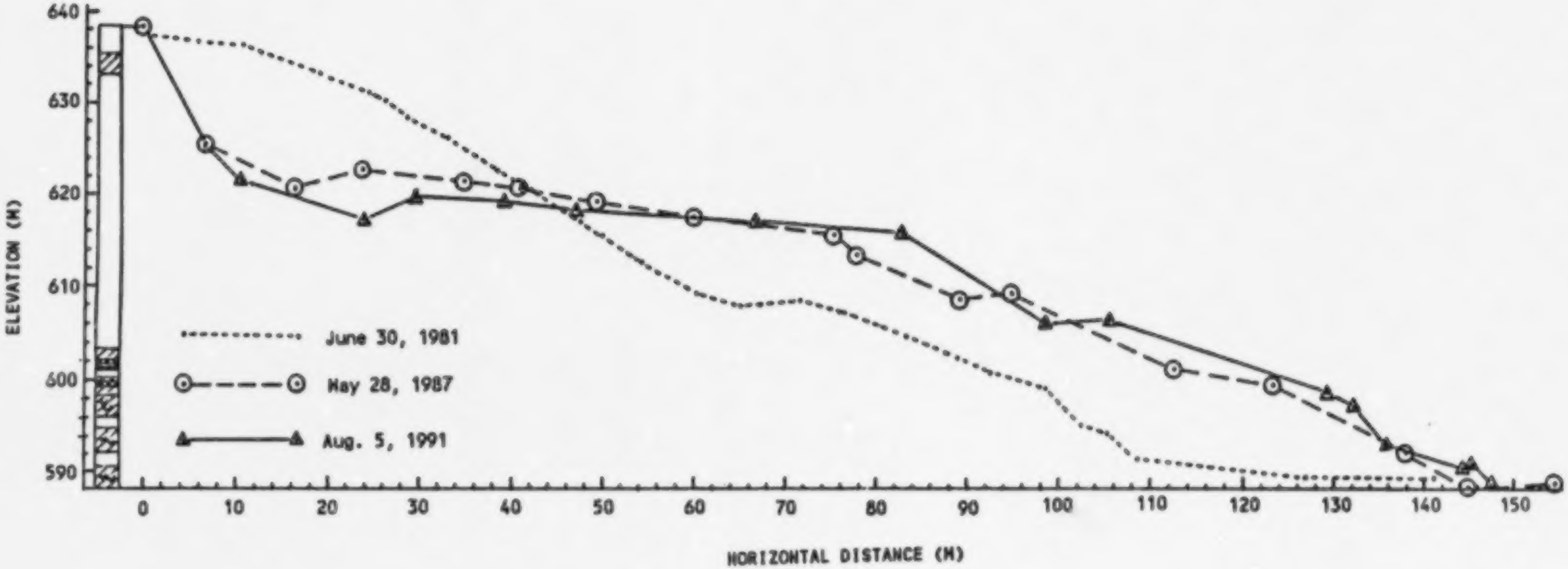


Figure 5.5 Change of profile of the East Slide.

increased in height and the toe had uplifted consistently from 1981 to 1991 profiles.

The rupture surface of the East Slide was estimated starting from both the toe and the rear scarp of the slide using the angle of scarp and movement vectors of the ground surface (Fig. 5.6) as described by Jakobson (1952) and shown in Fig. 5.7. The bedrock of the major portion of the rupture surface is bentonitic clay shale.

The most recent profile of the East Slide was drawn from the survey results and airphotographs of 1991 (Fig. 5.7). The East Slide is obviously a reactivation of an old landslide because the toe of the East Slide is clearly seen on the pre-landslide airphotographs (Chapter 3).

5.3 Subsurface exploration

5.3.1 Drilling Techniques

A drilling program was conducted from February 26 to March 7, 1991 by Alberta Environment. Three boreholes, ES-1, ES-2, and ES-2A were obtained from the drilling program. ES-2A was drilled only for piezometer installation.

A mobile B-61S, truck mounted drilling rig was used in conjunction with the 203mm hollow stem auger. A 76.2mm Shelby

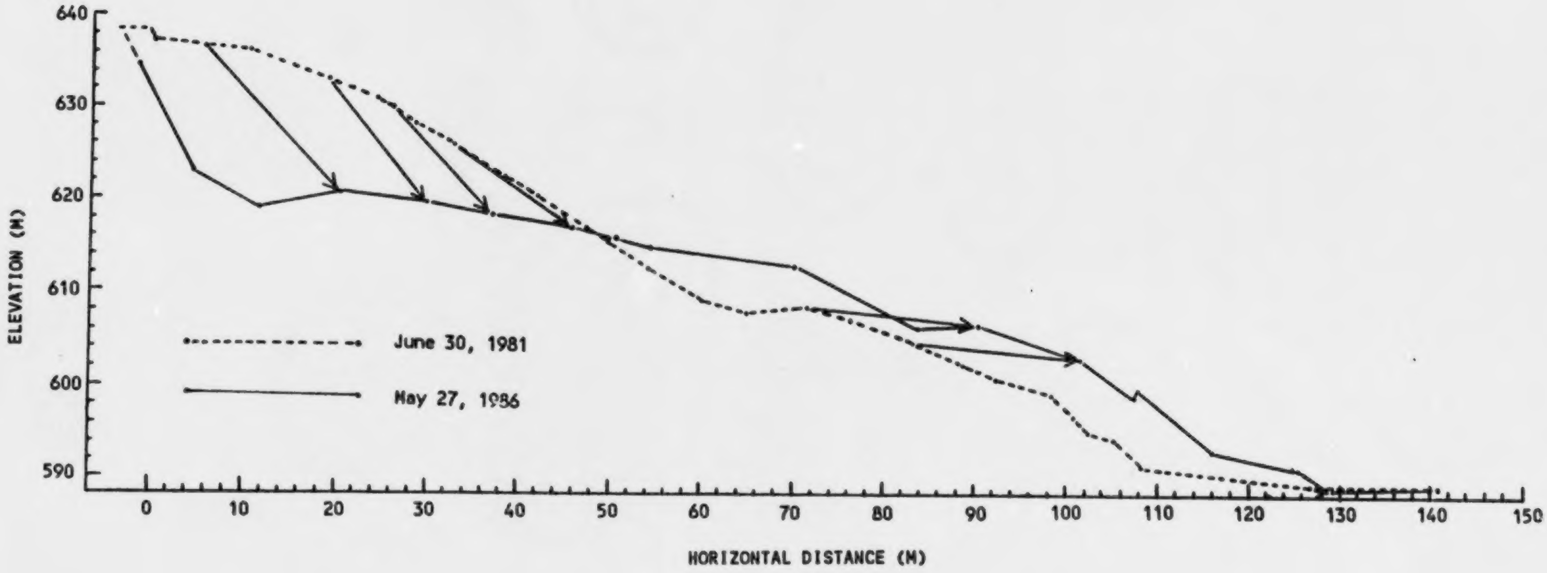


Figure 5.6 Movement vectors of the East Slide.

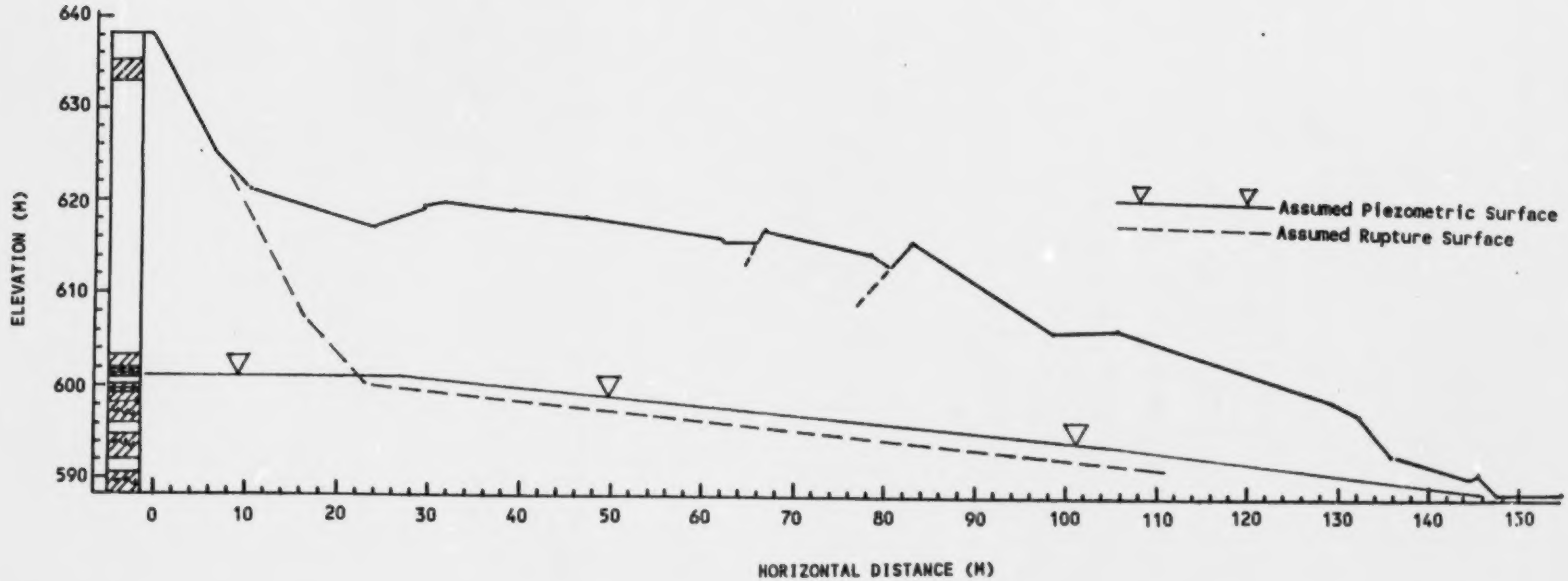


Figure 5.7 Profile of the East Slide.

thin wall tube sampler was used for sampling overburden materials. The thin wall tube sampler is one of the widely used undisturbed samplers for dry and undisturbed soils (Acker, 1974, p.63).

A CB19A core barrel was used for sampling bedrock using water for drilling fluid. Two 152.4mm casings were installed in ES-1 and ES-2 from ground level to 9.45m and 5.25m respectively to maintain clean open holes. The boreholes were drilled from the end of the casings to 35m below ground level using 120.6mm wet rotary rock bits without sampling. Sampling of the bedrock was conducted from 35m to 55m below ground level using the CB19A core barrel.

Samples of the bedrock and overburden materials were obtained, wrapped in plastic bags, packed in core boxes, and transported to the Alberta Environment laboratory. In the laboratory the samples were visually logged and initial index tests conducted. The remaining samples were waxed and stored in a moisture controlled room. Selected core samples were tested in the laboratory to determine the other engineering properties of the rock.

5.3.2 Boreholes

The three boreholes drilled are shown in Fig. 4.1 as ES-1, ES-2, and ES-2A. ES-1 is located on the crown of the South

Slide, and ES-2 and ES-2A on the crown of the East Slide. 25.4mm diameter plastic standpipes were installed in ES-1 and ES-2A for piezometer reading.

Boreholes ES-1 and ES-2 were drilled to depths of 55.05m and 55.5m respectively. The depths are well below the expected rupture surface according to the previous studies (Tweedie, 1976 and Mokracki, 1982).

Borehole logs for ES-1 and ES-2, as shown in Appendix 3, are based on the samples obtained and the subsequent detailed laboratory testing.

5.4 Results

Moisture content, wet unit weight, grain size distribution, and Atterberg limits profiles were obtained for ES-1 and ES-2 (Appendix 3). The depth of the weathering zone is about 10m. The clay shale in this zone contains gypsum lenses and crystals.

The core recoveries of the bedrock from ES-1 and ES-2 are 76% and 65% respectively. Poor core recoveries are mainly caused by crumbling of bedrock.

The rock samples show several other disturbed structures such as fractures, slickensides, and brecciation even though the boreholes are situated on the top of the valley wall in the area unaffected by slope movements. Brecciation is observed at depths of 41.25m and 44.35m in ES-1. A polished shearing surface which has an angle of 30° is observed at the depth of 39m in ES-1. A fracture zone exists at the depth of 42m in ES-2. Several slickensides and fractures are observed throughout the samples in both boreholes(Appendix 3).

ES-1 and ES-2 are correlated with each other using a sandstone as a key bed (Fig. 5.8). The dip of bedrock is almost horizontal but has a gentle slope to the west.

5.5 Discussion

From the observation of the boreholes, it is revealed that the depth of the weathering zone in the study area is about 10m. The strength of bedrock may have been reduced greatly due to the weathering process.

The presence of fractures, slickensides, and brecciation in ES-1 and ES-2 can be explained in several ways as discussed by several authors (Eigenbrod and Morgenstern, 1972; Morgenstern, 1977; Hutchinson, 1988); valley rebound, glacier ice-thrusting, and differential swelling of highly swelling bentonitic clay shale.

Matheson and Thomson(1973) stated that rebound of the

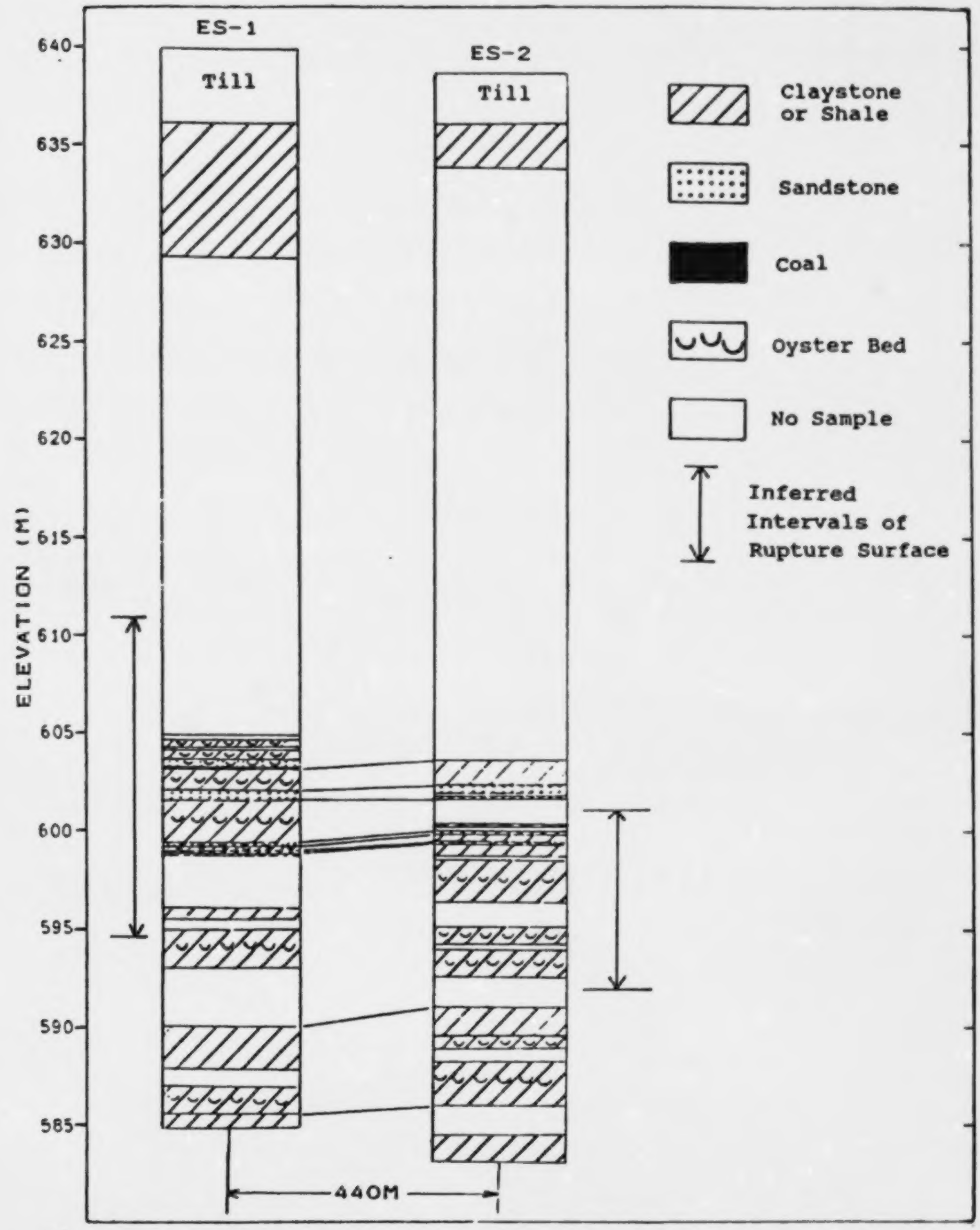

ES-1
ES-2
Till
Till
ELEVATION (M)
640
635
630
625
620
615
610
605
600
595
590
585
Claystone or Shale
Sandstone
Coal
Oyster Bed
No Sample
Inferred Intervals of Rupture Surface
440M

Figure 5.8 Stratigraphic profile of the South and East Slides.

valley floor occurred due to vertical stress relief and gave rise to a gentle anticlinal structure. The rebound locally influenced the dip of the beds and was accompanied by interbed slip which gave rise to gouge zones and brecciation. The evidence of valley rebound in the study area from three boreholes in the top of the North Slide used a sandstone bed as a key bed (Tweedie, 1976, p.44).

Ice-thrust terrains in western Canada have been recognized and reported by numerous workers (Hopkins, 1923; Slater, 1927; Gravenor and Meneley, 1958; Byers, 1959; Stalker, 1963; Kupsch, 1962; Christiansen and Whitaker, 1976; Moran et al., 1980; Shetsen, 1990). They should be recognized during site investigation because they cause slope instability (Knill, 1968; Sauer, 1978; Christiansen and Whitaker, 1976; Tsui et al., 1988; Hutchinson, 1988; Cruden et al., 1989).

Ice-movement direction in western Canada is mainly to the southwest as indicated by study of flutings and ice-thrust ridges (Gravenor and Meneley, 1958; Kupsch, 1962). Shetsen's (1990) Quaternary geology map of central Alberta included ice-movement directions in the study area (Fig. 5.9). This map shows that there are two ice-movement directions, one to the south and southwest and the other to the southeast but the major ice-movement direction is to the southwest.

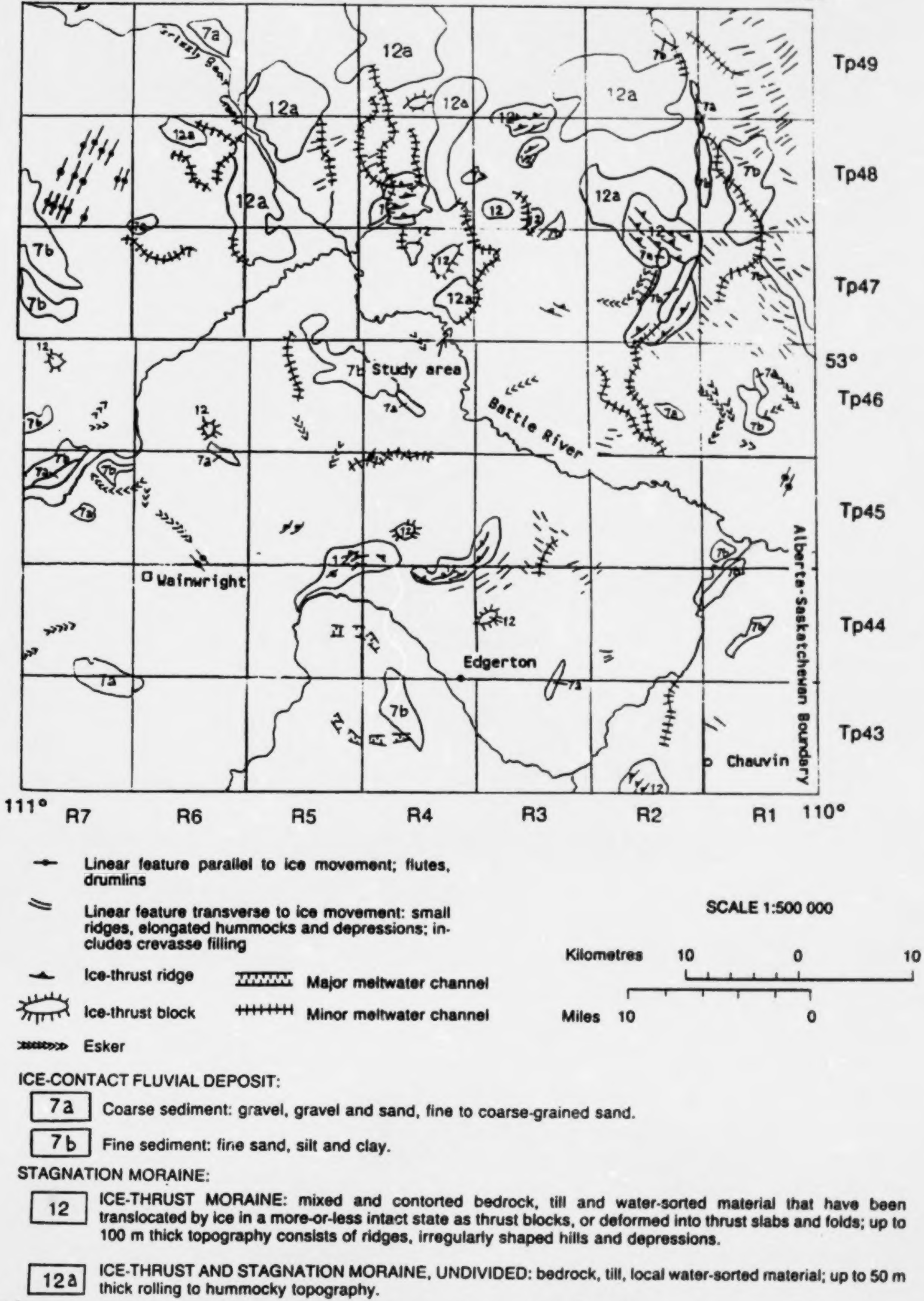

Tp49
Tp48
Tp47
53°
Tp46
Tp45
Tp44
Tp43
111°
R7
R6
R5
R4
R3
R2
R1
110°
Grizzly Bear
Study area
Battle River
Wainwright
Edgerton
Chauvin
Alberta-Saskatchewan Boundary
12a
12
7a
7b
Linear feature parallel to ice movement; flutes, drumlins
Linear feature transverse to ice movement: small ridges, elongated hummocks and depressions; includes crevasse filling
Ice-thrust ridge
Ice-thrust block
Esker
Major meltwater channel
Minor meltwater channel
SCALE 1:500 000
Kilometres 10 0 10
Miles 10 0
ICE-CONTACT FLUVIAL DEPOSIT:
7a Coarse sediment: gravel, gravel and sand, fine to coarse-grained sand.
7b Fine sediment: fine sand, silt and clay.
STAGNATION MORAINE:
12 ICE-THRUST MORAINE: mixed and contorted bedrock, till and water-sorted material that have been translocated by ice in a more-or-less intact state as thrust blocks, or deformed into thrust slabs and folds; up to 100 m thick topography consists of ridges, irregularly shaped hills and depressions.
12a ICE-THRUST AND STAGNATION MORAINE, UNDIVIDED: bedrock, till, local water-sorted material; up to 50 m thick rolling to hummocky topography.

Figure 5.9 Ice-movement direction in eastern and central Alberta.

Moran et al. (1980) concluded that conditions favorable for glacial thrusting included a frozen bed, pre-existing planes of weakness (such as bedding or jointing in sound rock or sediment), and decreased shear strength in rock or sediments (as a result of locally elevated pore-water pressure).

Evidence of deformation by glaciotectonics was recognized by Sauer (1978) in Saskatchewan. He suggested:

> " The ice-thrust phenomenon probably exists in a significant part of areas where glaciers have overridden clay shale bedrock or weakly indurated sandstone throughout the sedimentary basin of the Interior Plains, and other regions where the geology is similar to that in southern Saskatchewan."

He suggested that the thickness of the thrust blocks may be 100m or more.

Indications of the possible presence of glaciotectonic features in a certain area was suggested by several workers (Lamerson and Dellwig, 1957; Christiansen and Whitaker, 1976; Sauer, 1978):

> 1) slickensides or breccias in borehole samples; 2) omission of beds in one or a few holes; 3) repetition of a bed or beds in one or more holes; 4) ice-thrust ridges for an area of about 100 square miles (160.9 square kilometres) immediately surrounding the site; 5) folding or faulting at the outcrops which does not extend at depth.

Borehole samples in ES-1 and ES-2 show several breccias and slickensides. Ice-thrust ridges, ice-thrust blocks, and ice-thrust moraine are observed near the study area in Fig. 5.9.

Thomson and Tweedie(1978) also observed glacial ice thrust features, typified by brecciation and gently warping of the bedding planes, on the scarp face of the North Slide. For the above reasons, the presence of glaciotectonic thrusting in the study area is a distinct possibility.

Tsui et al. (1988) stated that three glaciotectonic settings were identified, namely, escarpment, valley, and plains based on the results of the terrain studies. The valley of the Battle River is partly preglacial according to the map of buried valleys in central and southern Alberta but the map shows that the valley of the study area is not preglacial (Stalker, 1961). The valley originated as a glacial spillway according to Gravenor et al.(1960, p.19). The bedrock topography of the valley wall in the study area follows surface topography but thalwegs which are interpreted as preglacial origin are not mapped in the area (Carlson and Topp, 1971; Carlson and Currie, 1973). Therefore, the study area belongs to the plains setting and the trends of ice-thrust ridges near study area lay perpendicular to the glacial advance. The thrusts and shears in ice-thrust features are commonly parallel to each other and dip in the direction opposite to the ice advance(Tsui et al., 1988). The dip of thrusts which were observed in Dirt Hills, Saskatchewan lay between 40° and 70° (Byers, 1959) but some glacial thrusts are flat (Cruden et al., 1989). However, the dips of thrusts in the study area are not known. The formation of a graben in the study area suggests that the rupture surface is almost horizontal.

Bentonitic clay shale is observed in both boreholes. Casagrande(1949) has suggested that the slickensides have been formed during the rebound process, because at this stage the shale was more brittle and therefore sensitive to irregular strains. Therefore, the differential swelling of the bedrock might cause the slickensides in the study area.

The slickensides, fractures, and brecciation of ES-1 and ES-2 may have reduced the shear strength of the bedrock significantly even though the origin of the shearing in the bedrock cannot be explained without ambiguity.

Another important feature is the occurrence of bentonitic clay shale. Bentonitic materials are observed from an elevation of 600m to the bottom of the borehole in ES-1 and may have occurred from an elevation of about 605m according to Tweedie's borehole logs and Atterberg limits test results. The strength parameters of the rock were considerably reduced if bentonitic materials were present either as seams or as admixtures (Locker, 1973). Therefore, the bentonitic material also may have reduced the shear strength of bedrock in the study area.

From the observation of samples in ES-1 and ES-2, it is concluded that the strength of the material in the study area must be low due to the minor structures such as slickensides, fractures, and brecciation and the existence of bentonitic material.

Chapter 6

Laboratory Testing Program

6.1 General

A laboratory testing program was planned to determine peak and residual strength parameters of the samples obtained from the bore holes, ES-1 and ES-2. In addition, consolidation tests performed on the samples checked preconsolidation pressures. Atterberg limit and hydrometer tests classified samples obtained from the bore holes and colluvium. The results and interpretation of the test program, along with brief descriptions of testing procedure are described in this chapter.

The tests were performed by the Alberta Environment Testing Laboratory, in accordance with the procedures detailed in ASTM(1990). The author drew up the testing program for the direct shear and consolidation tests and Mr. L.Kolody performed the tests in consultation with the author.

6.2 Index tests

Index tests and grain size analyses were performed on samples of ES-1, ES-2, and colluvium. The positions of the sample of the colluvium are shown in Fig. 4.1. The results of the tests are summarized in Table 6.1. Moisture content and wet unit weight profiles obtained for ES-1 and ES-2 are

Table 6.1 Summary of index tests.

Material	Depth (M)		Moisture Content (%)	Wet Unit Weignt (Kg/m³)	WL (%)	WP (%)	IP	Sand (%)	Silt (%)	Clay (%)	Activity
	ES-1	ES-2									
Till	0-3.8	0-3.0	4.5-13.8 (9.6)	1717-2292 (2064)	20-37 (26)	13-19 (14)	1-24 (12)	34-70 (51)	14-32 (25)	14-38 (24)	0.09-0.63 (0.46)
Siltstone	3.8- 10.6	3.0- 5.3	20.6-25.9 (23.4)	1943-2034 (1980)	59-71 (63)	23-27 (24)	33-47 (39)	4-16 (8)	52-71 (61)	13-43 (31)	1.08-2.50 (1.47)
Claystone	35.0- 54.5	35.0- 53.4	15.1-27.7 (22.8)	1911-2099 (2041)	131-162 (143)	27-33 (29)	104-132 (114)	0-2 (1)	26-41 (35)	57-73 (64)	1.51-2.16 (1.81)
Siltstone	54.5- 55.1	53.4- 55.5	24.7-29.3 (26.6)	1953-2015 (1983)	142-156 (149)	36-36 (36)	107-120 (113)	0-1 (1)	55-61 (58)	38-45 (41)	2.37-3.16 (2.77)
Colluvium	1.0				40-53 (46)	14-19 (17)	26-35 (29)	26-33 (30)	30-39 (35)	31-37 (35)	0.71-1.00 (0.84)

included in the borehole logs in Appendix 3.

6.2.1 Test results

Atterberg liquid and plastic limit tests for the clay shale and colluvium are shown in Table 6.1. The table shows the upper limit and lower limit of the values with the mean values within the brackets. The colluvium is CL and CH according to the Unified Soil Classification System (U.S. Army Engineer Waterways Experiment Station, 1960). The clay shale is classified as CL and CH.

The clay shale below 35m in ES-1 and ES-2 shows liquid limits ranging from 131 to 162. The values suggest a large percentage of montmorillonite present in the clay fraction(Grim, 1962, p.207). Many samples plot in the montmorillonites' region on Fig. 6.1.

The activity calculated for the colluvium ranges from 0.71 to 1.00 which are classified as normal according to Skempton (1953). The activity values of bedrock below 35m range from 1.51 to 3.16 which are classified as active and suggest high percentages of montmorillonite exist in the clay fraction.

6.3 Direct shear test

6.3.1 Testing procedure

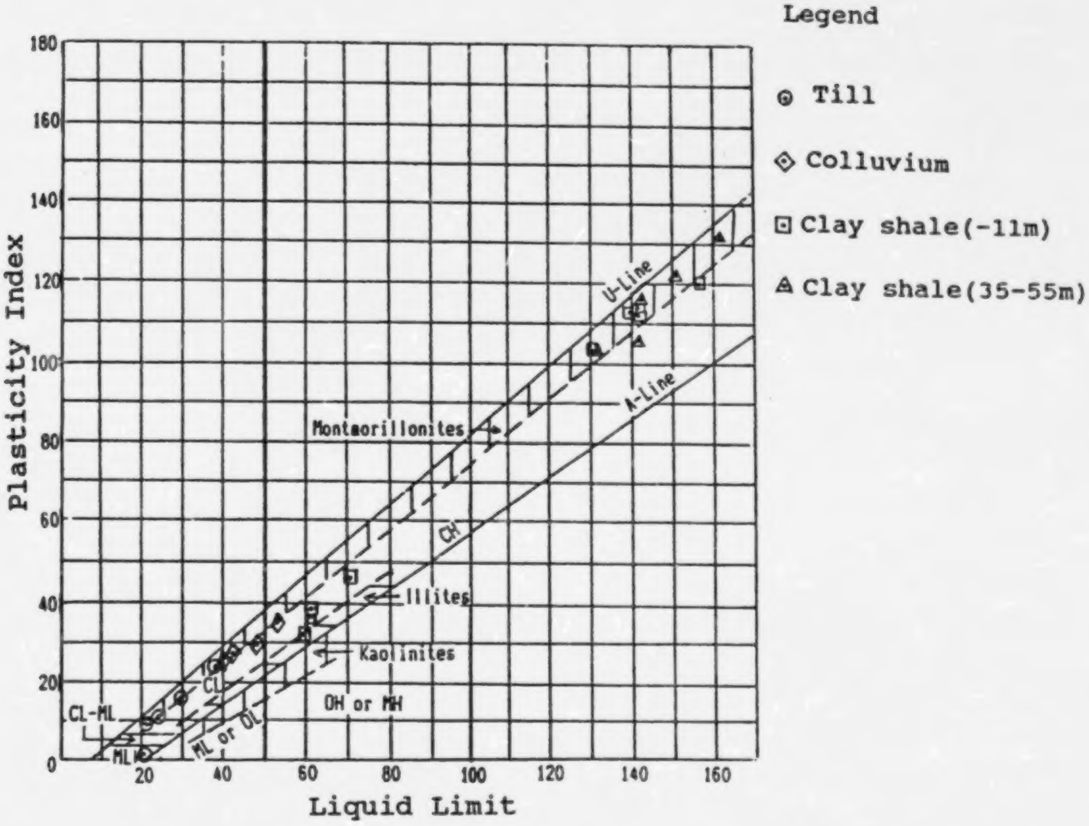


Figure 6.1 Casagrande's plasticity chart for laboratory classification of fine-grained soils and location of common clay minerals.

Direct shear tests determine peak and residual strength parameters of the material from ES-1. A reversal direct shear box, type K13, supplied by Clockhouse Co. was used for the tests. This machine accommodates the deformations of the order of centimetres which are required to reduce the strength of undisturbed samples to their residual values.

Test samples are chosen from suspected critical intervals in the borehole ES-1. Core samples were carefully carved to fit the shear ring which has a 50.8mm diameter. Tests are carried out on a set of specimens each at different normal stresses. Five stages of normal stress, 200, 450, 600, 800, and 1000 KPa are used for the tests. The sample is first allowed to consolidate under the selected normal pressure, until consolidation is completed and there is virtually no excess pore pressure remaining.

Samples are sheared very slowly to get their peak strength, at rates of 0.0013 mm/min, to ensure no pore pressure developed. Horizontal displacement, shear stress, vertical displacement, and effective normal stress values are recorded automatically using a computer system.

After the peak strengths are obtained, the samples are sheared in the reverse and then the forward directions for 10mm. This process is repeated several times until a constant value of the residual strength is reached. The rate of displacement is 0.46 mm/min.

6.3.2 Test results

The direct shear results are summarized in Table 6.2 for peak and residual parameters in ES-1. The test results on Mohr envelopes are illustrated in Fig. 6.2 and Fig. 6.3. Several different interpretations of the strength envelope are possible due to the variation of the strength results. The reason for this variation may be related to the inhomogeneity of samples and existence of fractures. The strength envelopes are estimated by a curve fitting method assuming zero cohesion for the residual angle of shearing resistance. The coefficients of determination for peak and residual parameters of clay shale between 38.55 and 38.68 are 0.83 and 0.95 and between 44.35 and 46.20 are 0.94 and 0.90 respectively. Residual strength values are obtained after 70 to 150mm displacement. The results of the residual strength test are shown in Appendix 4.

A phenomenon which occurs in each residual strength test is a different shear strength for the tension cycle and compression cycle. Cullen and Donald (1971) stated that some of this difference was possibly related to accumulation of apparatus errors, a lack of perfect particle reorientation on reversal, and inhomogeneities such as hard inclusions. The

Table 6.2 Summary of Shear Strength Tests

Material	Depth (M)	Peak Parameters		Residual parameters	
		C'(KPa)	ϕ'(°)	C'(KPa)	ϕ'(°)
Bentonitic Clay shale	38.5-38.9	219	22	0	12
Bentonitic Clay shale	44.4-46.2	7	35	0	9

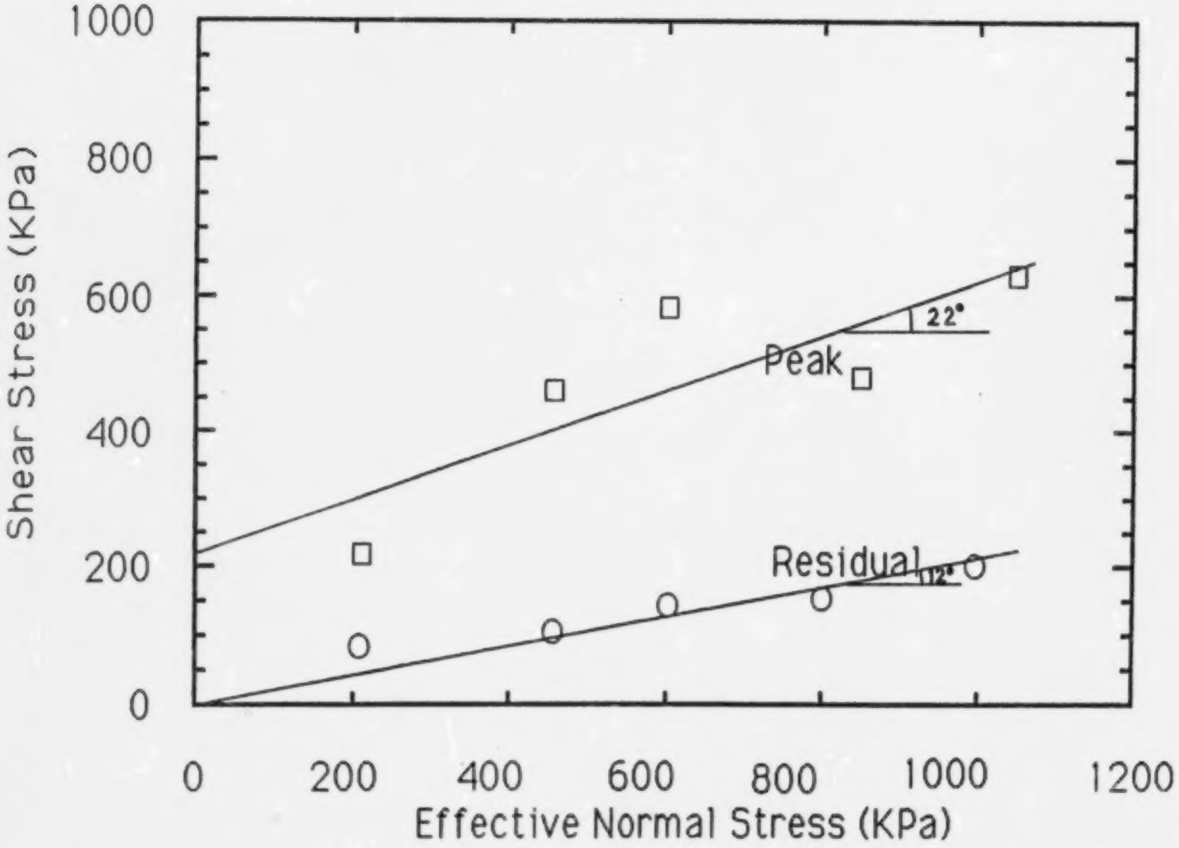


Figure 6.2 Mohr failure envelopes for direct shear tests on 38.35-38.68m interval.

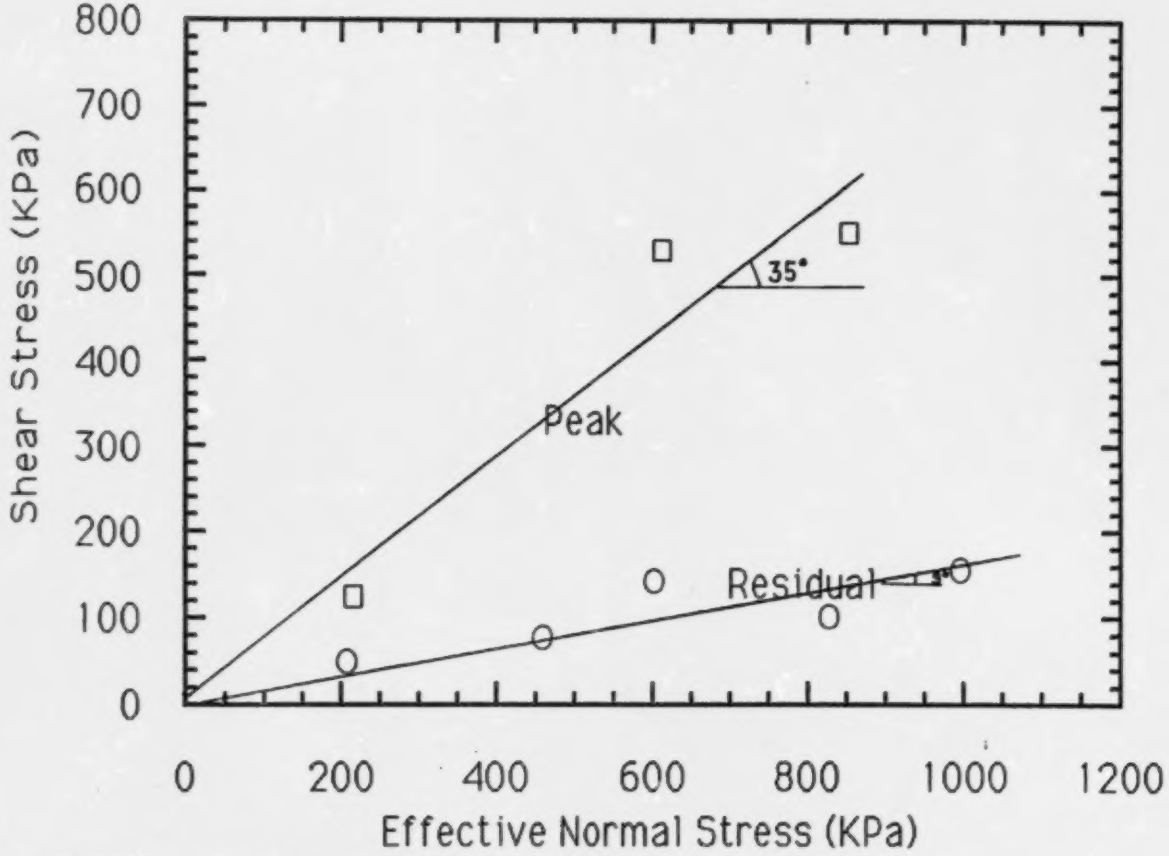


Figure 6.3 Mohr failure envelopes for direct shear tests on 44.35-46.20m interval.

average stress of the tension and compression cycles is taken for as the residual strength result in this test.

Kenney(1967) concluded that ϕ'r is dependent on soil mineralogy based on an extensive series of laboratory direct shear tests. He obtained ϕ'r values from 29° to 35° for the massive minerals like quartz, feldspar, and calcite. The general trend downwards from these minerals is illite or hydro-muscovite (ϕ'r=16° to 26°) to kaolinite(ϕ'r=15°) to the montmorillonites (ϕ'r<15°). The ϕ'r values of the study area, 9° and 12°, suggest high percentage of montmorillonites exist in the clay fraction. The ϕ'r values are in good agreement with previous work carried out on the bentonitic clay shales(Pennell, 1969; Thomson, 1971; Eigenbrod and Morgenstern, 1972; Tweedie, 1976).

6.4 Consolidation test

6.4.1 Testing procedure

To check the preconsolidation load a conventional consolidation test machine, type J41, supplied by Clockhouse Co. is used.

Test samples are chosen from the same intervals as direct shear tests. Swelling pressure is measured since the specimens have high swelling pressure. As soon as swelling is indicated, a small weight is added to the pan at the top of the weight hanger to bring the compression gauge back to the zero reading, or to within two or three divisions of it. If it is not enough, more weights are added; if too much, it is left for a little while in case swelling resumes. Continue to observe the compression gauge and add more weights as necessary to maintain the readings as close as possible to zero. After equilibrium is established, the consolidation test is started using several loading stages. The increment of load is doubled at each loading stage and continues until a linear plot of void ratio versus log of pressure becomes apparent. When the maximum required pressure was reached, unloading took place in a series of decrements.

6.4.2 Test results

Plotting of the void ratio/log pressure curve, and reporting of results, are given in Appendix 4 and Table 6.3.

The Casagrande(1936) method is used to estimate in situ preconsolidation pressure Pc'. The obtained Pc' ranges from 1000 to 4100 KPa. Based on the overburden at the sample site, the overconsolidation ratios of the samples are estimated to be between 1.3 and 3.5 (Table 6.3).

6.5 Interpretation of results

The results of index and direct shear tests consistently suggest that high percentages of montmorillonite exist in the

Table 6.3 Summary of consolidation tests.

Bore hole	Depth (M)	Swelling pressure (KPa)	Pre-consol. pressure (KPa)	Compre-ssive index	OCR	WL (%)	WP (%)	IP	Sand (%)	Silt (%)	Clay (%)
ES-1	38.34 -38.41	713	1800	0.058	2.2	107	24	83	3	69	28
	44.89 -45.01	252	1600	0.146	1.6	143	28	115	0	38	62
	54.55 -54.61	1279	2000	0.111	1.7	123	34	89	3	60	37
ES-2	35.25 -35.30	231	1000	0.169	1.3	106	29	77			
	45.41 -45.48	359	1800	0.121	1.9	122	27	85	0	40	60
	54.39 -54.49	1066	4100	0.122	3.5	108	32	76	0	69	31

bedrock below 35m. Swelling pressures as high as 1279 KPa have been measured below 54.5m in ES-1, which is equivalent to a bedrock thickness of about 65m. Therefore, the values of swelling pressure also suggest a large percentage of montmorillonite present in the bedrock below 35m (Table 6.3).

The activity values in these intervals ranging from 1.51 to 3.16 are classified active according to Skempton(1953). He gave the following activity values for the clay minerals; sodium montmorillonite, 7.2: calcium montmorillonite, 1.5; illite, 0.9; and kaolinite, 0.33 to 0.46. Therefore, the values of the intervals ranging from 1.51 to 3.16 also suggest a high percentage of montmorillonite, especially Ca-montmorillonite, exist in the clay fraction. This result is well matched with Tweedie's mineralogical and physico-chemical analyses which had a value of clay size portion of 76%, of which, approximately 75% was composed of montmorillonite in the bentonitic clay shale (Tweedie, 1976)

Grim(1962, p.219) expected that active clays would have relatively high water-holding capacity, high compaction under load, low permeability, and low resistance to shear, with cohesion largely responsible for the strength. Very active clays therefore, would be expected to cause problems for the engineer.

The upper limit of this active clay zone in ES-1 and ES-2 is not certain because samples were not obtained continuously. From the correlation with the Tweedie's borehole logs, the elevation of the upper limit of this active clay zone may lie about 605m.

The presence of bentonite reduces the strength parameters of the rock considerably. Thomson and Morgenstern (1977) stated that the presence of weak layers such as bentonite or bentonite-rich fine-grained strata readily accounted for the dominance of the translational failure mode of the valley wall in southern Alberta. Therefore, the presence of bentonitic clay shale may be the main factor causing the stability problem in the study area.

Steiner et al. (1972, Fig.5; Fig.8) drew the contour map of moisture contents and regional rank distribution of Alberta coals and the coal in the study area plots in the lignite field. This is well matched with the field observation of Hume and Hage (1941). Hacquebard (1977, Fig.3-3) calculated the amount of eroded sediment over oil and natural gas fields in the plains of Alberta using a figure which was derived from the data of German mines and boreholes. Nurkowski (1984) provided a linear relationship between original depth of burial and calorific value for the Alberta plains coal. Results of the analysis of calorific value (moist mineralmatter-free basis, in KJ/Kg) on depth of burial (DOB, in m), yields: CVmmmf=14748+6.25DOB. However, he recommended using this equation for calorific value ranging from 22000 to 29000 KJ/Kg. The above range does not include the lignite of the study area, which has a calorific value of between 14654 and 19306 KJ/Kg. Therefore, Hacquebard's figure (1977, Fig.3-3) is used to calculate original depth of burial of the coal in the study area.

Hacquebard (1977) estimated the moisture content of near-surface coals in Wainwright which is located near the study area as 33%. Therefore, original depth of burial of the coal is about 830m from his figure. From this result, it is estimated that approximately 790m of strata have been removed from the study area during Tertiary times. Therefore, the OCR of the samples based on geologic evidence should range from about 15.6 to 23.6. Comparison with the test results suggests that the fabric due to overconsolidation has been destroyed possibly by ice thrusting, valley rebound, swelling due to bentonitic clay shale or softening.

Seed, et al. (1962, Fig.13) developed the relationships between the percentage of clay sizes, the activity of the clay, and the percentage of swell under a 1-psi surcharge of a sample compacted at optimum water content to maximum density in the Standard AASHO Compaction Test. The samples in the study area between 35m and 55m show very high swelling potential (Fig. 6.4). This is well matched with the direct measurement of swelling pressure. The samples in ES-1 and ES-2 show several slickensides and the study area was eroded about 790m from the coal study. Therefore, the rebound of the study area due to very high swelling potential of the bedrock and erosion of overburden materials may have caused the destruction of the fabric due to overconsolidation in the study area.

The possible influence of ice thrusting and valley rebound on the bedrock of the study area was presented in Chapter 5.

Fissured overconsolidated clays lose their strength with time due to a process of softening was described by Terzaghi (1936) and subsequently by Skempton (1948, 1970). Softening occurs as a result of water infiltration in the fissures leading to swelling and associated weakening of the clay. Eventually, unless overall failure intervenes, the end product of such a softening process must be a clay reduced essentially to its normally consolidated condition (Skempton, 1948). Therefore, the softening of the bedrock in the study area may have caused the destruction of the fabric due to overconsolidation.

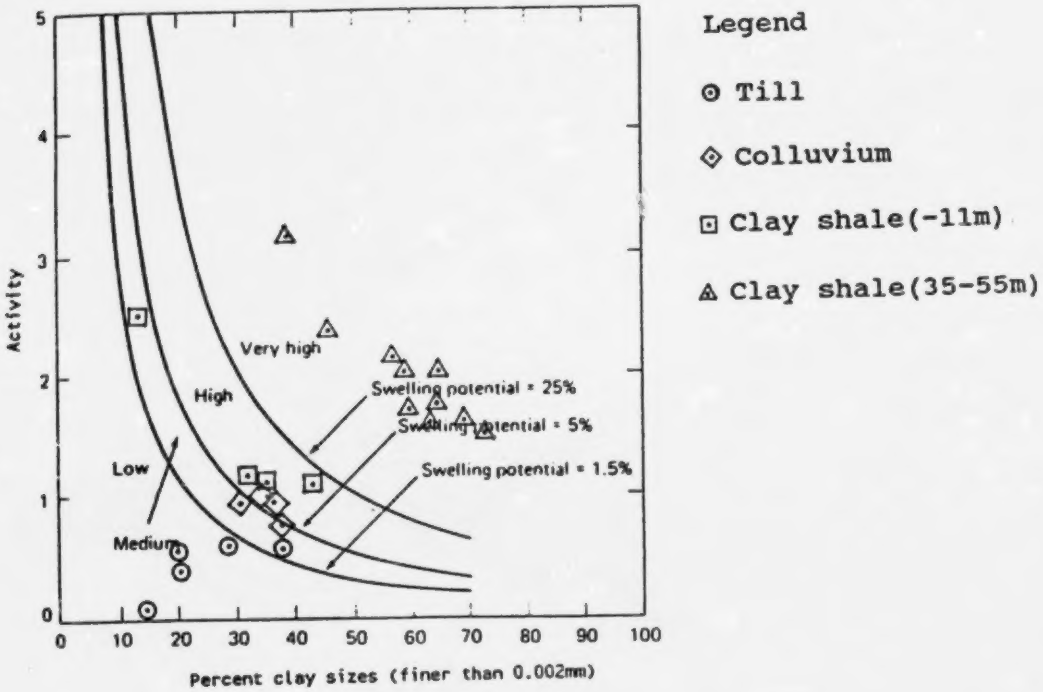


Figure 6.4 Classification chart for swelling potential.

It may be concluded from the laboratory testing program that the presence of bentonitic clay shale, which is indicated by Atterberg limit tests, activity, direct shear tests, and high swelling pressures, may be the main factor causing the stability problem in the study area. In addition, although the origin of the destruction of the fabric due to overconsolidation in the clay shale cannot be stated without ambiguity, it may be attributed to the slope movements of the area.

Chapter 7

Stability Analysis

7.1 General

From the time that major slope movement first occurred in 1974, the landslides have grown in area and continue to grow. Results of stability analyses, performed on the South Slide by Tweedie(1976), suggested that residual strength parameters were being mobilized along the major portion of the horizontal part of the rupture surface($\phi'=8°$), with peak angles of shearing resistance($\phi'=23°$), but essentially zero cohesion in the backscarp materials. In the case of the East Slide, the combination of peak angles of shearing resistance($\phi'=23°$), with zero cohesion along the backscarp coupled with residual angles of shearing resistance ($\phi'=8°$) and zero cohesion acting along the rupture surface results in a factor of safety near unity (Mokracki, 1982). In order to investigate the change of strength parameters, a post-slide analysis is carried out in this section.

The calculations of the factor of safety of the Edgerton landslides have been carried out using the general non-circular limit equilibrium analysis described by Morgenstern and Price (1965). The method proposed by them satisfies all the boundary and equilibrium conditions, including moment equilibrium of the individual slices.

The surface profiles used in the analysis are those surveyed in August 1991, but some of the more pronounced surface irregularities have been included from the airphoto interpretation.

The piezometric levels in the slide masses are not known, therefore, the piezometric lines are assumed to exist at the elevation determined by Tweedie (1976) in the South Slide. The effect of changing the piezometric level is analyzed for the each slide.

The subsurface stratigraphy shown in Fig. 5.8 is simplified and is considered as three basic material types, i.e., till, clay shale, and bentonitic clay shale. Tweedie(1976) and Mokracki(1982) subdivided the clay shale into two different material type, brown highly weathered silty clay shale which is the part of the rupture surface in the backscarp and toe area and stiff grey fissured silty clay shale. However, the clay shale was not divided into two different material types in this analysis because most of the weathered silty clay shale in the scarp area was exposed and the strength parameters used for the weathered silty clay shale near the toe by Tweedie were almost same as those of bentonitic clay shale. The strength parameters of the till were not considered in the analysis because the till was completely exposed in the scarp area. Table 7.1 summarizes the

Table 7.1 Summary of material properties used in stability analysis

Material	Bulk Unit Weight (KN/m^3)	Strength Parameters				Strength parameters used in stability analysis	
		Peak		Residual			
		C'	φ'	C'	φ'	C'	φ'
Till*	18.83	-	-	-	-	0	24
Clay Shale*	19.81	160	23	0	19	0	14**
Bentonitic Clay Shale	20.02	7	35	0	9	0	8

* Data for till and clay shale from Tweedie(1976)

** Data from Thomson(1970)

Notes: Units of cohesion are KPa. Angles of shearing resistance are in degrees.

material properties which are used in the stability analysis. Since the rupture surfaces have moved by the dormant and recent slope movements, residual strength parameters are mainly used for the analysis. In addition to the material properties shown in Table 7.1, several other combinations of the strength parameters are also analyzed.

The location of the rupture surface of the slide is estimated based on the profile study of the each slide, movement vectors of the control points, and Tweedie's (1976) slope indicator study. Two different modes of rupture surface are analyzed for the South Slide, i.e., a flat lying rupture surface and a stepped rupture surface. The stepped rupture surface is assumed from the uplift movement vectors in the region A (Fig. 5.4).

7.2 Stability analysis results

7.2.1 North Slide

The results of the stability analysis performed on the North Slide are summarized in Table 7.2 and are discussed in the following paragraphs.

A factor of safety of 1.30 is obtained for trial surface 1 which has residual strength parameters along the sub-horizontal portion of the rupture surface, and zero cohesion in the backscarp but with peak angles of friction (Fig. 7.1, a). Assuming residual strength parameters for both the backscarp and the rupture surface, a factor of safety of 1.05 is obtained and a factor of safety of 0.97 if $\phi'=8^{\circ}$ is assumed for the bentonitic clay shale.

The effect of an increasing cohesion in the backscarp is investigated in trial surface 4. If cohesion of 47.9 KPa is applied to the clay shale, a corresponding factor of safety of 2.18 is obtained. This shows that the factor of safety is very sensitive to cohesion in the backscarp.

When the slope movement of the North Slide first occurred in 1974, the toe of the North Slide was assumed to be located a horizontal distance of about 180m from the scarp, which had a steepened slope angle. This area was called the 'old toe' because the recent toe of the North Slide advanced far below the area. However, it is not certain whether the rupture surface of the North Slide is extended to the new toe area(trial surface 1-4) or just surface colluvium material is involved in the slope movement(trial surface 5). Therefore, slope analysis is performed using the old toe and a factor of safety 1.11 is obtained using residual strength parameters (Fig. 7.1, b).

The effects of decreasing the piezometric level are demonstrated in trial surface 6-9, and resulted in an increase

Table 7.2 Summary of stability analysis (North Slide)

Trial Sur. No.	Till		Clay shale		Bentonitic clay shale		Safety Factor	Remarks
	C'	ϕ'	C'	ϕ'	C'	ϕ'		
1	0	24	0	23	0	9	1.30	Peak friction angle in clay shale
2	0	24	0	14	0	9	1.05	Residual
3	0	24	0	14	0	8	0.97	
4	0	24	47.9	14	0	8	2.18	Cohesion in clay shale
5	0	24	0	14	0	8	1.11	Rupture surface through old toe
6	0	24	0	23	0	9	1.53	Peak friction angle in clay shale
7	0	24	0	14	0	9	1.21	Residual
8	0	24	0	14	0	8	1.13	
9	0	24	0	14	0	8	1.32	Rupture surface through old toe

Notes: Units of cohesion are KPa. Angles of shearing resistance are in degrees. Decreasing piezometric level in trial surface 6-9.

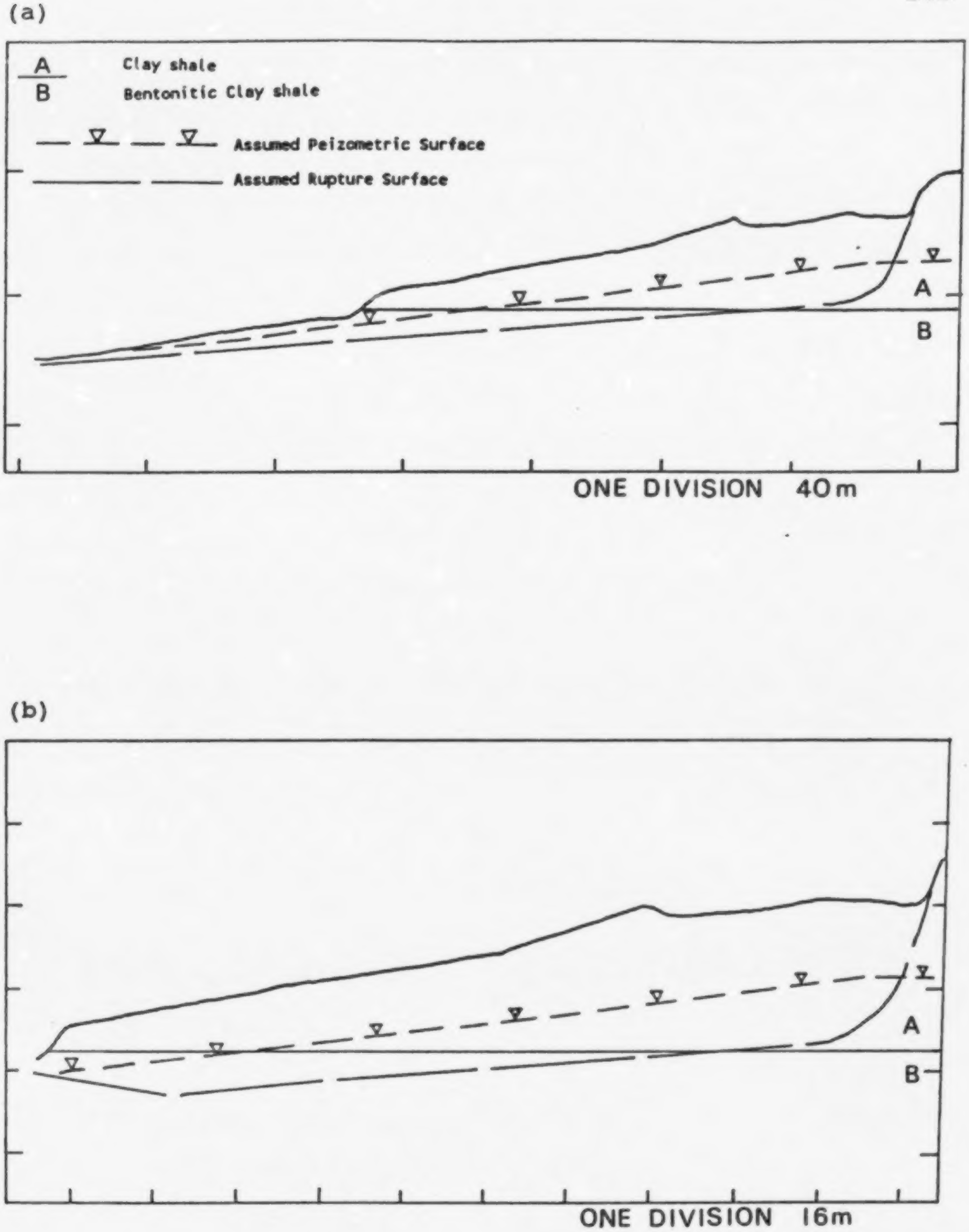
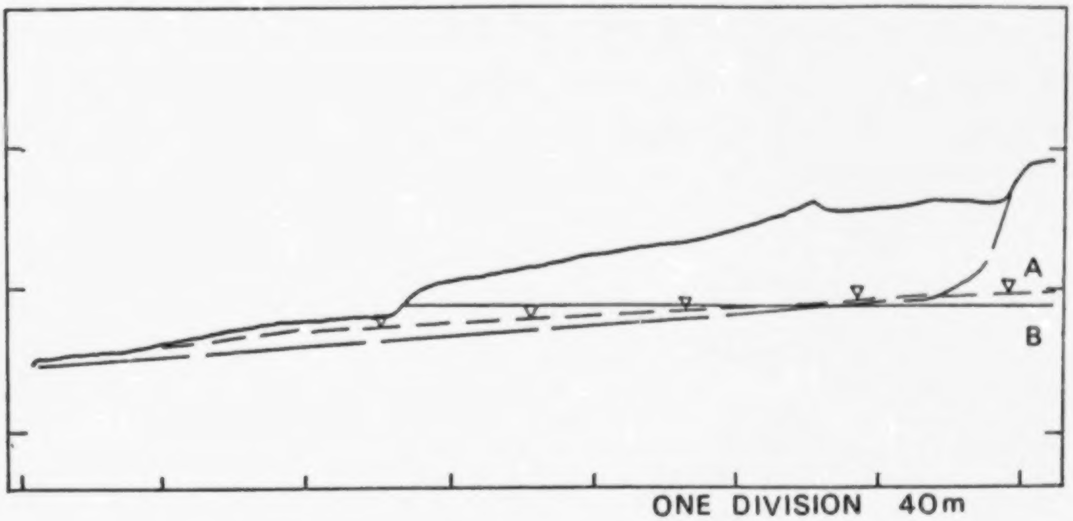

(a)
A
B
Clay shale
Bentonitic Clay shale
Assumed Peizometric Surface
Assumed Rupture Surface
A
B
ONE DIVISION 40m
(b)
A
B
ONE DIVISION 16m

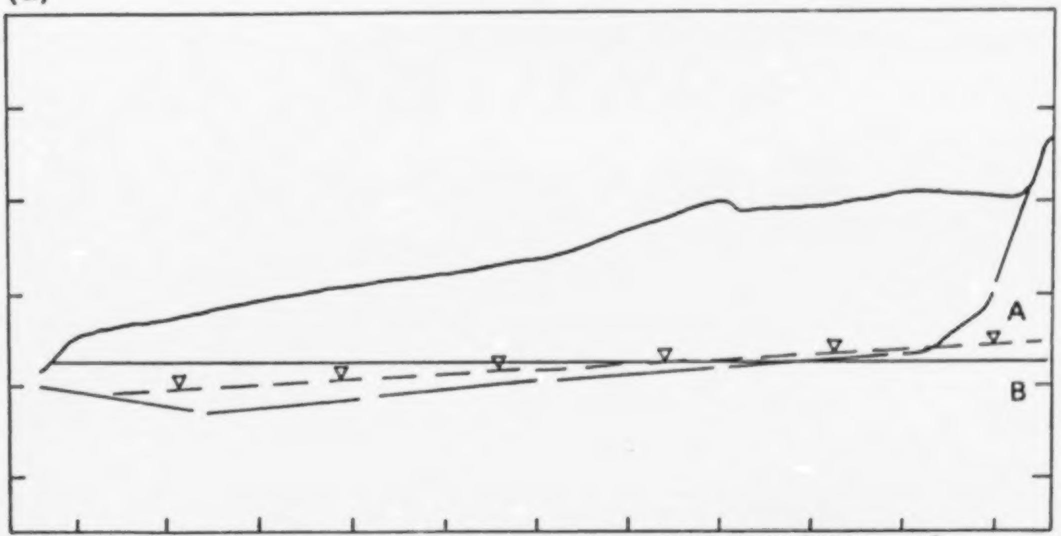
Figure 7.1 Profiles of the North Slide used in the stability analysis.

Figure 7.1 (continued)

(c)


A
B
ONE DIVISION 40m

(d)


A
B
ONE DIVISION 16m

in the factor of safety in each case (Table 7.2, Fig. 7.1, c-d).

The preceding points indicate that the factor of safety is sensitive to the strength parameters of the clay shale, and also the piezometric level. It may be concluded from the stability analysis of the North Slide, that the most likely solutions giving a factor of safety close to unity are trial surfaces 2 and 3. This indicates that residual angles of shearing resistance with zero cohesion are being mobilized in the backscarp, with residual friction angles and zero cohesion acting in the sub-horizontal rupture surface, and rupture surface exposed in the new toe area.

7.2.2 South Slide

The results of the stability analysis performed on the South Slide are summarized in Table 7.3. This slide was analyzed by Tweedie(1976) but an infinite slope was assumed because the toe of the South Slide was not exposed at that time. Since the toe was exposed in 1986, the actual position of the toe is used in this analysis and the effect of the changing the position of the toe is reviewed.

A factor of safety of 1.12 is obtained for trial surface 1 which specifies residual strength parameters for both the backscarp and the rupture surface and a factor of safety of

1.05 is obtained for trial surface 2 if $\phi'=8°$ is assumed for the bentonitic clay shale (Fig. 7.2, a). The effect of an increasing friction angle in clay shale is investigated in trial surface 3-4. The friction angles of 19° and 23° are applied to the clay shale and corresponding factors of safety of 1.29 and 1.43 are obtained. This shows that the factor of safety is sensitive to the angle of shearing resistance of the backscarp material.

The effect of changing the position of the toe is demonstrated in trial surface 5 (Fig. 7.2, b). In this analysis, a factor of safety of 1.02 is obtained using the position of the toe estimated by Tweedie(1976). Therefore, the results of the slope analysis using the estimated position of the toe in 1975 may not be much different from the results using the actual position of the toe.

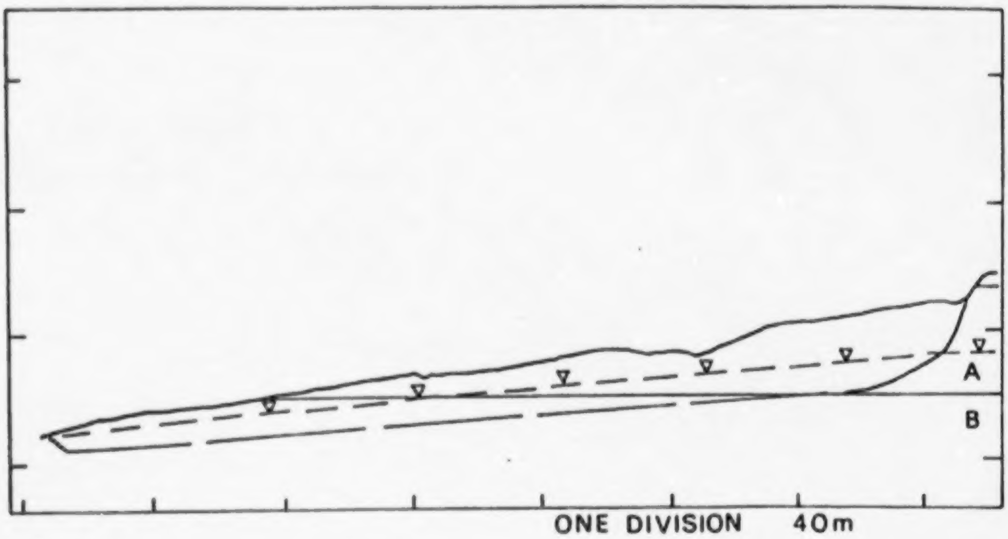
The effect of a stepped rupture surface is investigated in trial surfaces 6-7 (Fig. 7.2, c-d). The factors of safety of 1.21 and 1.56 are obtained for residual and peak friction angles of clay shale respectively. Indeed, to obtain a factor of safety close to unity requires assuming a residual angle of shearing resistance of 7° along the sub-horizontal rupture surface, with a residual angle in the backscarp. This analysis gives a factor of safety of 1.05 (trial surface 8).

Table 7.3 Summary of stability analysis (South Slide)

Trial Sur. No.	Till		Clay shale		Bentonitic clay shale		Safety Factor	Remarks
	C'	ϕ'	C'	ϕ'	C'	ϕ'		
1	0	24	0	14	0	9	1.12	Residual
2	0	24	0	14	0	8	1.05	
3	0	24	0	19	0	9	1.29	Increasing friction angle in clay shale
4	0	24	0	23	0	9	1.43	
5	0	24	0	14	0	8	1.02	Rupture surface through estimated toe in 1975
6	0	24	0	14	0	9	1.21	Residual
7	0	24	0	23	0	9	1.56	Peak friction angle in clay shale
8	0	24	0	14	0	7	1.05	Decreasing friction angle in bentonitic clay shale
9	0	24	0	23	0	9	1.84	Decreasing piezometric level about 5m

Notes: Units of cohesion are KPa. Angles of shearing resistance are in degree. Stepped rupture surface in trial surface 6-9.

(a)


A
B
ONE DIVISION 40m

(b)

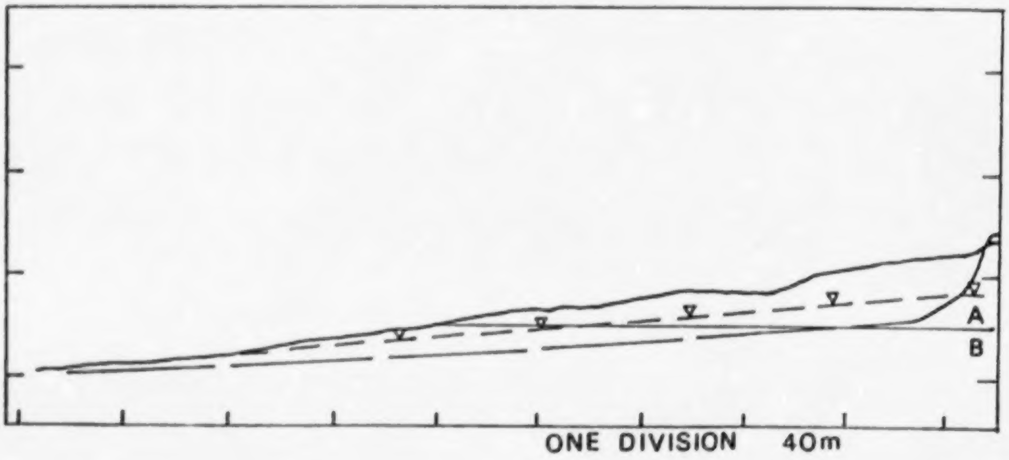
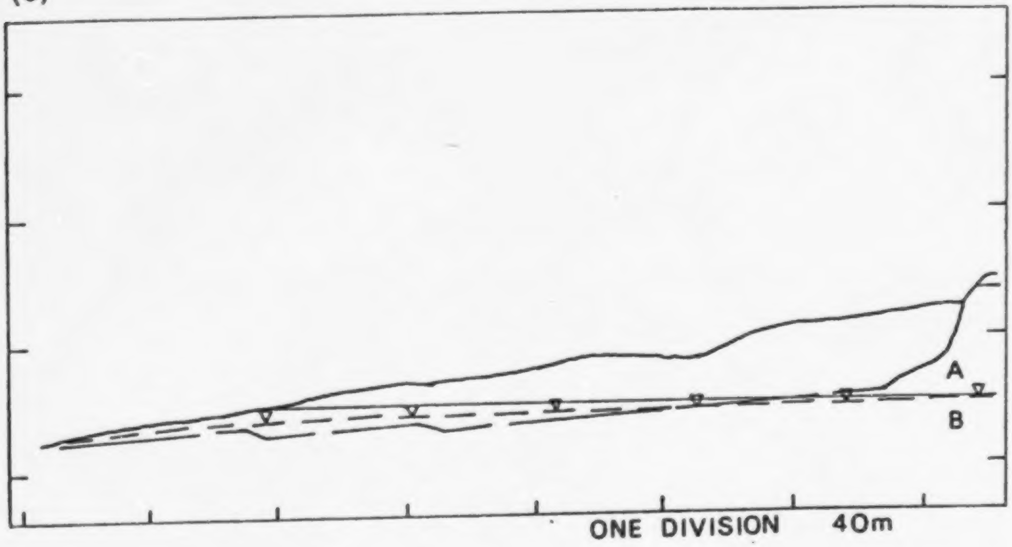

A
B
ONE DIVISION 40m

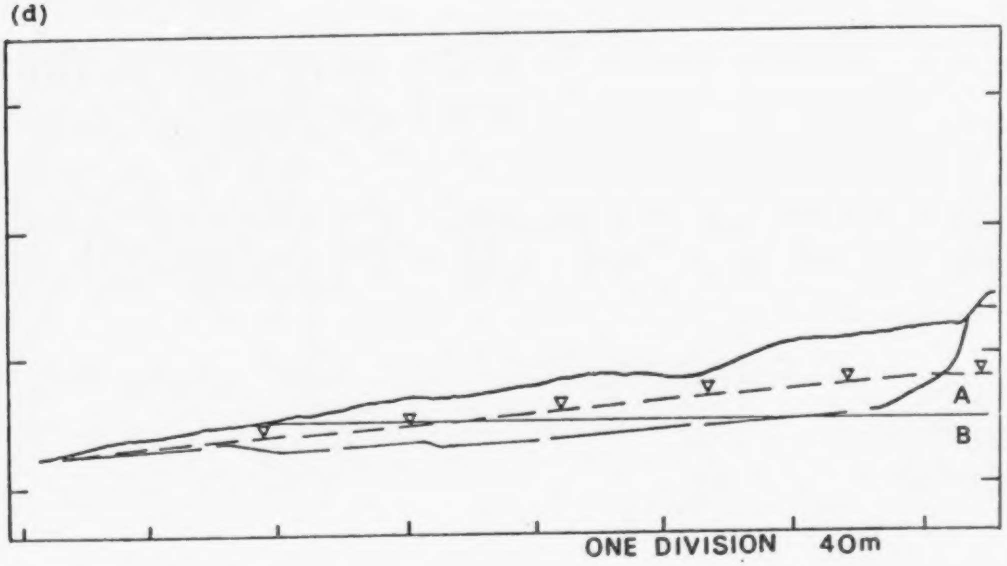
Figure 7.2 Profiles of the South Slide used in the stability analysis.

Figure 7.2 (Continued)

(c)


A
B
ONE DIVISION 40m

(d)


A
B
ONE DIVISION 40m

The effect of decreasing the piezometric level is demonstrated in trial surface 9, and factor of safety of 1.84 is obtained (Fig. 7.2, c).

The preceding points indicate that the factor of safety of the South Slide is sensitive to the shearing resistance of the backscarp material, the piezometric level, and also the shape of rupture surface, and is insensitive to the estimated position of the toe. It may be concluded from the stability analysis of the South Slide that the most likely solutions giving a factor of safety close to unity uses trial surface 2. This indicates that residual angles of shearing resistance with zero cohesion are being mobilized in the backscarp, with residual friction angle and zero cohesion acting in the sub-horizontal rupture surface.

7.2.3 East Slide

The results of the stability analysis performed on the East Slide are summarized in Table 7.4 and are discussed in the following paragraphs.

A factor of safety of 0.98 is obtained for trial surface 1 which has residual strength parameters for both the backscarp and the rupture surface (Fig. 7.3, a). Assuming residual strength parameters along the sub-horizontal rupture surface, zero cohesion in the backscarp, and a peak angle of friction of $\phi'=23°$ for the clay shale (trial surface 2), a factor of safety of 1.06 is obtained and a factor of safety of 0.96 if the friction angle of the bentonitic clay shale is assumed as 8° (trial surface 3).

The effect of an increasing friction angle along the sub-horizontal rupture surface is investigated in trial surface 4. A factor of safety of 1.36 is obtained if an angle of shearing resistance of 12° is specified in the bentonitic clay shale, and a peak angle of friction of 23° in the clay shale. This demonstrates that the factor of safety is sensitive to the strength parameters along the sub-horizontal rupture surface.

The effect of an increasing cohesion in the clay shale is demonstrated in trial surface 5. Cohesion of 47.9 KPa is applied to the clay shale and a corresponding factor of safety of 1.25 is obtained.

The effect of increasing the piezometric level is demonstrated in trial surface 6-7 because the piezometric level 1-5 is relatively low compared to those of the North and South Slides. Increasing the piezometric level by about 1m near the toe area resulted in the factor of safety of 1.02 (Fig. 7.3, b). Increasing the piezometric level to almost the same elevation as the North and South Slides resulted in the factor of safety of 0.92 (Fig. 7.3, c). A factor of safety of

Table 7.4 Summary of Stability Analysis (East Slide)

Trial Sur. No.	Till		Clay shale		Bentonitic Clay shale		Safety Factor	Remarks
	C'	ϕ'	C'	ϕ'	C'	ϕ'		
1	0	24	0	14	0	9	0.98	Residual
2	0	24	0	23	0	9	1.06	Peak friction angle in clay shale
3	0	24	0	23	0	8	0.96	
4	0	24	0	23	0	12	1.36	Increasing friction angle in bentonitic clay shale
5	0	24	47.9	23	0	9	1.25	Cohesion in clay shale
6	0	24	0	23	0	9	1.02	Increasing piezometric level about 1m near toe area
7	0	24	0	23	0	9	0.92	Increasing piezometric level
8	0	24	0	14	0	9	0.86	
9	0	24	0	14	0	8	1.89	No water

Notes: Units of cohesion are KPa. Angles of shearing resistance are in degree.

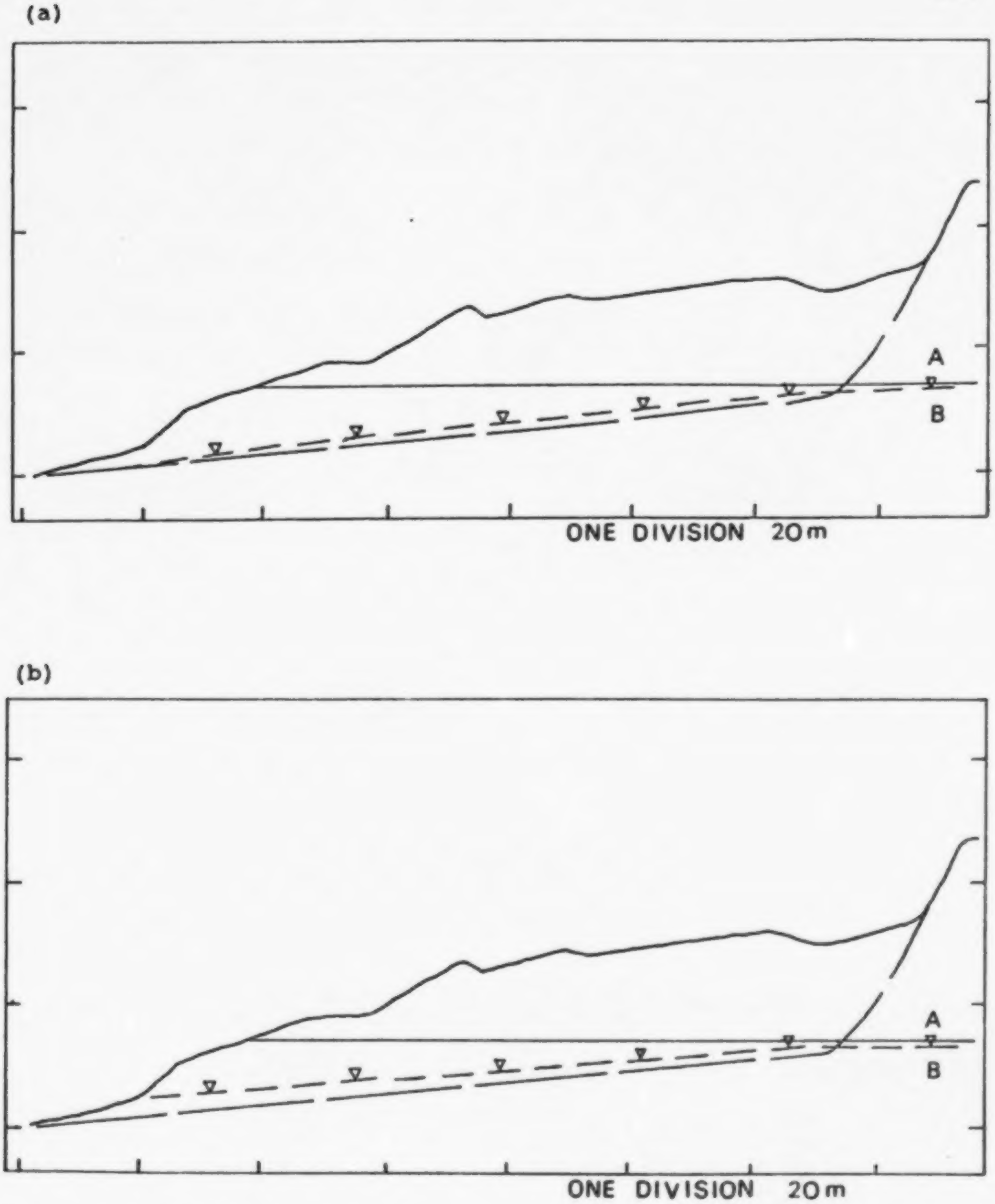
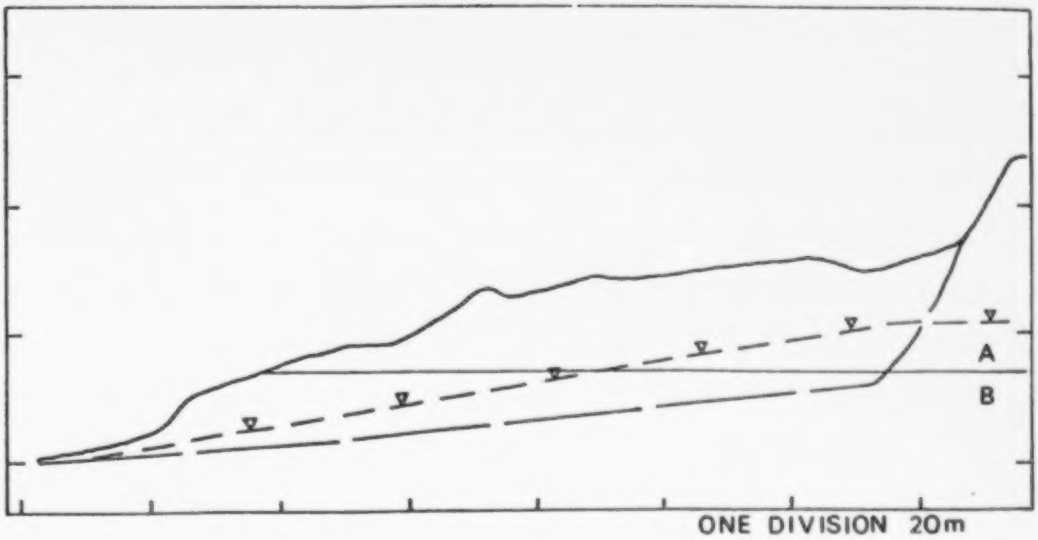

(a)
A
B
ONE DIVISION 20m
(b)
A
B
ONE DIVISION 20m

Figure 7.3 Profiles of the East Slide used in the stability analysis.

Figure 7.3 (Continued)

(c)


A
B
ONE DIVISION 20m

1.89 is obtained (trial surface 9) assuming no water in the slide mass.

The preceding points indicate that the factor of safety is sensitive to the strength parameters along the essentially horizontal portion of the rupture surface, piezometric level, and cohesion of the clay shale and is least sensitive to the friction angle of the clay shale. It may be concluded from the stability analysis of the East Slide, that the most likely solution giving a factor of safety close to unity uses trial surface 1. This indicates that residual angle of shearing resistance with zero cohesion are being mobilized in the backscarp, with residual friction angle and zero cohesion acting in the sub-horizontal rupture surface. However, the piezometric level of trial surface 1 is assumed to be relatively low compared to those of the North and South Slides.

7.3 Discussion

The results of stability analyses indicate that the factor of safety is sensitive to the strength parameters of the clay shale which occurs on the steeply inclined portion of the rupture surface, piezometric level, and friction angle along the essentially horizontal portion of the rupture surface. In addition, it may be concluded that the most likely solutions giving factors of safety close to unity are residual angles of shearing resistance($\phi'=14°$) with zero cohesion in the main scarp materials, with residual friction angles($\phi'=8°$) and zero cohesion in the sub-horizontal rupture surface.

The results suggest that all the materials are now at, or very close to, their residual strength along the rupture surface and pore pressures acted as a triggering mechanism for the landslides in the study area.

Skempton and Hutchinson(1969) stated that most stiff (overconsolidated) clays showed a marked decrease in strength from peak to residual, resulting partly from the particle orientation effect and also from an increase in water content due to dilatancy within the zone of shearing. The distinct decrease of strength along the rupture surface may result in the post-failure movements in the study area. Actually, the toe of the South Slide was not exposed until 1986 even though the main scarp developed in 1974. Mokracki(1982) found that the velocities for control points upslope were higher than for those control points located near the present toe of the South Slide. Table 7.5 also shows the movements of three control points on the profile of the South Slide, which are estimated from the profiles in Fig. 5.3 and drawn in Fig. 5.4. The result indicates that the velocities for control points upslope are higher than for the control point located downslope near the toe. The differences of movements within

Table 7.5 Summary of relative displacements for control points on the profile of the South Slide (Aug., 1986 - Aug., 1991)

Control Point	Horizontal Displace. (M)	Vertical Displace. (M)	Total Displace. (M)	Annual Displace. (M/Yr)
10	+4.30	+0.75	4.36	0.87
12	+3.05	-0.60	3.11	0.62
13	+2.55	0.00	2.55	0.51

Notes: + Displacement Downhill
- Displacement Uphill

the slide masses result in the formation of tension cracks in the region A (Fig. 5.4). The result suggests that the strengths of the materials along the rupture surface were not reduced to their residual values simultaneously. The strengths of the materials may have reduced in sequence from the scarp to the toe area. However, the process may be caused by the gradual spreading of surface cracks which allow run off to penetrate because the slope movement is the reactivation of dormant landslide.

The effect of the tension cracks to the slope stability may be damaging but it has not been considered in the slope analysis because the computer program of Morgenstern and Price's method did not accommodate tension cracks. According to the results of ground surveying (Appendix 2), the horizontal displacements of stations 300 and 400 along the profile of the South Slide (Fig. 4.1) are 0.42m and 0.40m and vertical displacements are +0.009m and +0.038m respectively. The results suggest that the shear strength reduces to the residual values along the entire length of the rupture surface and strain distribution is uniform along the surface.

Table 7.6 shows the measurements of piezometric level in the boreholes. The results indicate that the water level is much lower than that of Tweedie's (1976). The low water level in August, 1991 may be related to the low precipitation

Table 7.6 Measurements of piezometric level from the ground in the boreholes (M)

Date	ES 1	ES 2A
May 14, 1991	36.28	37.60
August 5, 1991	36.48	37.52
April 17, 1992	36.66	37.50

(Appendix 1). Visual observation of the site in April, 1992 revealed thaw completed in the fields and high groundwater caused by snow melting had dissipated along the lower part of the slide, which was indicated by dryness of discharge area. Therefore, the highest water level may be expected during March as indicated by Tweedie and summer which is equivalent to the highest precipitation period (Appendix 1). The factor of safety of the slope may be the lowest during those periods of the year.

The formation of a minor scarp of the North Slide was not included in the stability analysis because a profile through the minor scarp was not obtained. The formation of a minor scarp is likely to increase the tendency of a slope to fail because the length of rupture surface along which shear strength can be mobilized is reduced. In addition, surface water can flow directly into the slide masses of the North Slide and many tension cracks in the lower parts of the slide help surface water infiltration into the slide masses. The formation of a minor scarp and the concentration of surface water in the North Slide masses may result in the most active slope movement in the area among three slides.

It may be concluded from the stability analyses that the post-failure movement of the area is closely related to the reduction of strengths to their residual values from the scarp to the toe, seasonal high groundwater levels, and surface water. In addition, the formation of tension cracks may contribute to the instability of the area in the future.

Chapter 8

Conclusions and Recommendations

8.1 Conclusions

This investigation of the slope movements which occur on the valley wall of the Battle River, northeast of Wainwright, Alberta leads to the following conclusions.

1. The slope movements of the area are reactivations of dormant landslides. Airphoto interpretation and field evidence suggest that movement of the landslides proceeded from the scarp to the toe. Therefore, causes of the landslides might lie in the scarp area. Airphoto interpretation and field observation suggest that surface water flowed directly into the North Slide scarp. Since the bedrock in the scarp area was highly weathered and brecciated down to about 10m, the surface water which flowed into the slope might have softened the materials gradually. The slope movement was eventually triggered by the increase in pore pressures induced in the slope, following the abnormally high spring runoff in 1974. Forest clear-cutting behind the North Slide scarp may have contributed to the increase of pore pressures in the scarp area.

2. Study of the area's coal suggests about 790m of rock was

eroded during the Tertiary. Comparison with consolidation tests suggests that the rock fabric due to overconsolidation has been destroyed. Borehole samples in ES-1 and ES-2 show fractures, slickensides, and brecciation even though the boreholes are situated on the top of the valley wall unaffected by slope movements. Possible causes of these features are glacier ice-thrusting, valley rebound, and differential swelling of highly-swelling bentonitic clay shale. The disturbed structures may have reduced the shear strength of the bedrock significantly even though the origin of the shearing in the bedrock cannot be explained without ambiguity. These features may have contributed to the instability of the area in the past and may cause instability in the future because the strength parameters of the materials are reduced to their residual states before the slope movements occur.

3. It may be concluded from the laboratory testing program that the presence of bentonitic clay shale, which is indicated by Atterberg limit tests, activity, direct shear tests, and high swelling pressures, may be the main factor causing the stability problem in the area.

4. When the slope movements first occurred in the North and the South Slides, the displacements did not develop sufficiently to produce a continuous rupture surface

emerging at the toe. The movements of the depleted masses were taken up by compression and slight bulging of their accumulations. The bulging of the ground caused extension cracks in the slide masses, which increased infiltration of surface water. Since the bedrock in the study area is bentonitic clay shale, the infiltration of surface water might cause swelling of clay shale by absorption of water and therefore, decreasing strength. Furthermore, pore pressures might build up along the pre-sheared rupture surface, causing continuous slope movements showing advancing failure modes. Therefore, the formation of tension cracks in the slide mass may result in advancing failure modes when the bentonitic material is involved in the rupture surface.

5. The two new boreholes on the crowns of the South and East Slides are correlated with each other using a sandstone as a key bed. Stratigraphy in the South and East Slides is similar to that in the North Slide.

6. The South Slide gradually expanded southwards. By 1980 it may have impeded drainage down its south flank which may have affected the stability of the mass to the east. In addition, the toe of the East Slide formed across the creek and overlapped the toe of the South Slide. Therefore, the South Slide may have affected the stability of the East

Slide.

7. The directions of the slope movements in the three landslides are different and the landslides overlap one another. Since the bedrock of the study area dips gently to the southwest, the rupture surfaces of the landslides do not follow a single bedding plane.

8. Results of post-slide stability analyses, performed on the Edgerton landslides suggest that residual strength parameters are being mobilized along the entire rupture surfaces. In addition, factors of safety are sensitive to piezometric levels. Therefore, the factor of safety of the area may be the lowest when water levels are highest.

9. The results of airphoto interpretation and control surveying suggest that the toes of the North and the East Slides are advancing at rates of about 1m/year. The formation of extension cracks within the South Slide mass also suggests that the South Slide may advance in the future.

8.2 Recommendations

The following recommendations are suggested for the further study of the area.

1. A profile through the minor scarp of the North Slide should surveyed for a more accurate stability analysis for the North Slide.

2. Since factors of safety are sensitive to piezometric levels, several piezometers are necessary for each slide to measure pore pressures. It is suggested that piezometric readings be taken from the spring thaw to the end of summer.

3. Slope indicators should be installed in front of the toes of the displaced material of North and East Slides to determine the depths and material properties of the rupture surface and relationship with the present rupture surfaces.

4. In order to get movement vectors along each profile of the slides, the positions and identification labels of control points should not be changed and the labels of control points at the stakes should be marked periodically to maintain clarity of the letters. If new stakes are needed due to the change of slope angle or loss of old stakes, they should be differentiated from the original stakes.

5. The results of control surveying gave valuable data for the slope movements. Therefore, it should be done periodically.

6. Control points should be surveyed at least three times, spring following spring thaw, end of July, and end of September each year to detect the time of slope movements.

7. To record the changes of surface features, air photographs of the area should be taken annually until slope movements become negligible. The best time of the year to take air photographs is just after snow melt and before vegetation grows. The best time of the day is between 11:00 and 13:00 when the sun angle is high. It is recommended that at least one airphoto which covers the whole study area be taken.

8. Regional airphoto interpretation, measurements of piezometric levels, observations of borehole samples, and laboratory test results of the samples should be obtained for other areas near the study area to understand why this is the only active slope movement in the area.

9. Paleontologic data, electric-log data, and more complete recovery of core from bore holes are needed in order to accomplish more accurate geologic correlation in the study area.

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Appendix 1

Precipitation Record - Paradise Valley, Alberta (mm)

Table A.1 Precipitation record - Paradise Valley, Alberta(mm)
(53° 07' N, 110° 21', 660m A.S.L.)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1962	24.6	34.3	31.0	20.3	35.3	99.3	104.9	15.7	21.1	15.0	34.8	22.4	458.7
1963	26.4	28.4	30.2	30.7	42.7	110.7	185.9	58.7	12.7	17.5	17.8	15.0	576.7
1964	35.6	15.0	11.7	27.2	63.8	25.9	44.5	51.8	96.8	22.9	25.9	17.3	438.4
1965	31.8	29.7	11.9	11.9	77.7	156.7	44.2	78.7	18.5	1.0	19.1	12.7	493.9
1966	33.5	9.4	25.1	14.5	11.7	18.0	85.3	66.8	11.7	2.0	34.5	16.0	328.5
1967	21.3	18.0	22.4	21.1	24.6	53.1	35.1	45.2	1.8	29.2	33.8	30.7	336.3
1968	22.6	13.5	20.8	35.1	21.1	55.9	100.8	98.6	99.3	27.7	5.1	27.9	528.4
1969	41.4	14.0	4.6	31.5	35.6	13.5	122.4	27.9	66.5	17.5	15.2	29.7	419.8
1970	12.4	13.5	37.1	5.6	27.2	159.0	126.5	9.4	13.0	49.3	28.7	23.9	505.6
1971	38.6	9.9	24.1	8.4	28.2	81.5	124.9	58.9	10.7	14.7	22.1	37.3	459.3
1972	20.3	23.6	34.8	30.2	17.5	33.0	58.7	48.5	49.8	8.1	25.4	17.3	367.2
1973	13.7	19.1	23.1	42.2	16.3	117.9	83.3	118.4	27.2	23.9	44.7	20.1	549.9
1974	42.7	12.2	25.9	23.9	33.5	117.9	75.7	26.2	25.9	5.3	0.3	15.0	464.5
1975	17.3	14.5	42.4	53.8	37.1	96.8	54.4	75.4	3.8	24.4	6.9	25.9	452.7
1976	9.7	23.4	31.0	18.0	45.2	122.9	35.6	46.0	29.0	5.8	3.0	32.0	401.6
1977	21.6	5.0	7.2	33.8	139.8	31.2	72.8	28.5	63.9	6.1	10.0	36.7	456.6
1978	13.7	5.2	7.0	63.1	70.8	41.2	77.3	55.0	48.8	7.8	22.1	9.6	421.6
1979	8.5	29.9	11.6	22.6	34.7	107.0	84.2	25.5	19.9	10.0	6.6	26.7	387.2
1980	39.0	15.6	31.1	5.6	37.6	93.6	77.1	86.7	27.1	9.6	5.3	38.4	466.7
1981	21.0	4.1	14.5	21.8	18.0	48.9	66.2	20.8	10.4	9.2	5.4	12.3	252.6
1982	25.8	13.2	41.4	18.9	46.6	36.3	106.3	56.9	37.3	26.2	17.3	10.2	436.4
1983	10.4	20.5	23.6	6.7	12.1	68.5	114.8	38.0	67.0	12.6	35.5	14.5	424.2
1984	14.2	22.4	12.5	27.1	74.0	90.0	37.5	37.8	84.3	35.2	26.6	17.5	479.1
1985	14.6	9.8	3.6	51.3	37.9	94.2	22.4	103.1	24.1	17.6	8.2	33.5	420.3
1986	21.4	7.1	34.2	20.0	58.6	66.4	136.0	6.4	51.8	11.0	48.8	11.7	473.4
1987	13.9	10.1	24.9	35.2	21.8	40.7	119.0	70.0	22.8	4.8	14.8	14.3	392.3
1988	9.2	13.8	38.0	3.4	41.8	120.7	39.7	120.3	43.2	12.5	11.8	15.3	469.7
1989	31.8	7.0	7.2	7.1	49.3	97.8	56.8	86.0	48.1	6.9	18.6	33.4	450.0
1990	14.3	18.1	21.1	15.6	15.1	82.5	70.0	53.6	6.8	13.7	19.5	18.3	348.6
1991	12.6	20.4	7.6	51.5	40.7	42.6	32.2	23.8	6.4	31.5	7.7	22.8	299.8
Aver. 1951-1980	23.2	17.2	23.5	27.5	38.4	76.7	76.6	51.8	33.1	16.2	19.6	23.3	427.1

Appendix 2

Results of Ground Surveying using an E.D.M. Instrument

Table A.2 Results of ground surveying (m)

Station No.	Northing	Easting	Elevation	Year
710	5874014.1003	527888.0246	687.3909	1990
41	5874012.3650	527831.7600	687.1625	
1	5874032.9851	527888.3827	688.0149	
11	5874033.1960	527897.8132	688.2645	
2000	5874022.5365	528122.3503	694.0588	
2010	5874039.1805	529378.0304	665.8712	
2020	5874036.3786	530610.7404	669.0665	
2030	5874052.5209	531839.8100	673.2605	
2040	5874054.6916	532234.3635	670.9896	
2050	5874063.0749	534251.7116	648.1736	
100	5874071.5045	534289.4157	647.2215	
200	5873955.8944	534479.0343	635.3673	
300	5874040.7405	534584.7436	614.9164	
400	5874075.7640	534698.0907	597.1694	
500	5874014.7135	534912.3864	587.7867	
600	5874344.0065	534819.4194	566.5054	
700	5874470.5392	534684.8941	583.5635	
800	5874212.8400	534603.5899	605.3565	
900	5874368.1270	534536.3622	618.4775	
1000	5874291.0729	534424.7035	640.1977	
1100	5874073.9292	534424.2760	640.8189	
100	5874071.5045	534289.4157	647.2216	1991
1000	5874291.0800	534424.6923	640.1905	
2006	5874077.5495	534428.2536	640.7509	
1101	5874073.7994	534426.9596	640.7990	
201	5873958.4565	534475.6303	635.4968	
300	5874040.7731	534585.1678	614.9085	
400	5874075.7174	534698.4939	597.1351	
500	5874014.9182	534912.4662	587.7561	
600	5874344.2227	534819.8316	566.4896	
700	5874470.5537	534684.8551	583.5708	
900	5874368.1407	534536.3444	618.4743	
800	5874213.3911	534606.1712	604.8204	
110	5874063.0903	534231.6495	647.9121	
120	5874059.2684	533230.6360	652.4841	
130	5874060.5416	533110.0071	657.9478	
140	5874054.7680	532220.3985	672.2274	
150	5874053.0851	531835.4277	674.4028	
160	5874046.5055	530646.8669	669.7958	
170	5874039.6563	529380.4849	667.0177	
180	5874029.8230	528128.3929	695.3567	
190	5874024.7058	527884.4278	688.9556	
1	5874032.9871	527888.4424	687.8896	
11	5874033.1941	527897.8640	688.1366	
41	5874012.3791	527831.8260	687.0573	
710	5874014.1065	527888.0846	687.2792	
100	5874071.5045	534289.4157	647.2215	1992
1000	5874291.0774	534424.6948	640.1893	
2006	5874077.5504	534428.2339	640.8268	
1101	5874073.7994	534426.9580	640.7983	
200	5873956.0514	534479.1985	635.2459	
201	5873958.4866	534475.6772	635.5183	
300	5874040.7731	534585.2960	614.9021	
400	5874075.6989	534698.5903	597.1265	
500	5874014.9862	534912.5099	587.7370	
600	5874344.2968	534820.0396	566.4688	
700	5874470.5358	534684.8571	583.5607	
900	5874368.1245	534536.3492	618.4686	
800	5874213.4638	534606.5912	604.7400	

Table A.3 Movement vectors of stations (m)

Station Number	1990 - 1991		1991 - 1992	
	Hor. Move.	Azimuth	Hor. Move.	Azimuth
100	-	-	-	-
200	0.17	42°45'	0.06	60°00'
300	0.43	85°35'	0.13	90°00'
400	0.41	96°40'	0.10	100°20'
500	0.22	21°30'	0.08	32°45'
600	0.47	62°20'	0.22	70°25'
700	-	-	-	-
800	2.64	77°55'	0.43	80°10
900	-	-	-	-
1000	-	-	-	-
1100	-	-	-	-

Notes: - No detectable movement

Stations located on Fig. 4.1

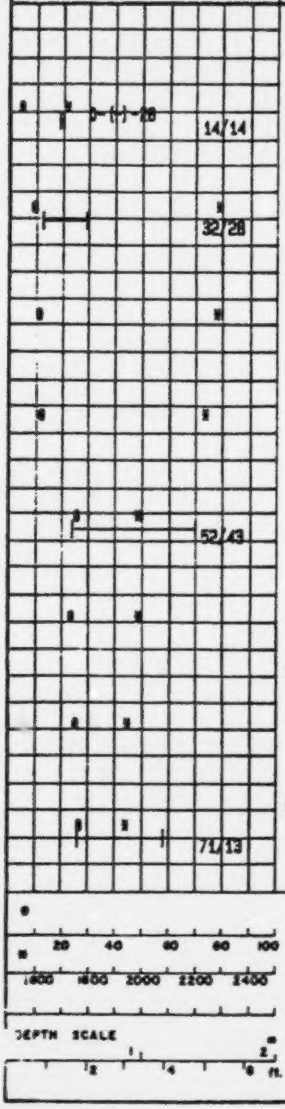
Appendix 3

Borehole Logs

Alberta ENVIRONMENT
DEVELOPMENT & OPERATIONS DIVISION
GEOTECHNICAL SERVICES LABORATORY

PROJECT EDGERTON SLIDE
SITE
HOLE No. ES 1 ELEV.
LOCATION
TECHNOLOGIST AS LK DATE DRILLED 26 Feb 1991

BOREHOLE AND TEST LOG



DEPTH (m)	SYMBOL	DESCRIPTION	SAMPLE	OTHER INFORMATION
	☐	TOPSOIL		RIG: MOBILE B-61S AUGER TYPE: 203mm HCA
1	▒	SM-med br, coal & calcite spots, occ pebble to 5mm, cal, roots.	◿	PP= (-) Rec= .34m/.40m
	▨	CL(TILL)-hard, med br, coal & CS chips, pebbles to 20mm. roots, calcite streaks, cal.	◿	PP= 383+ Rec= .24m/.30m
2	▨	as above, dk br.	◿	PP= 383+ Rec= .16m/.40m
3	▨	as above, dk br.	◿	PP= 383+ Rec= .17m/.40m
4	▨	CLAYSTONE-hard, mtld med & dk br, rust coated frac, gyp crystals, SS frags.	◿	PP= 383+ Rec= .23m/.40m
	▨	as above, gyp lenses.	◿	PP= 383+ Rec= .26m/.30m
5	▨	as above, gyp lenses.	◿	PP= 383+ Rec= .28m/.30m
6	▨	as above, gyp lenses & crystals.	◿	PP= 383+ Rec= .28m/.30m

☐	▦	▒	▨	▥	◿	☒
TOPSOIL OR NO SAMPLE	GRAVEL	SAND OR SANDSTONE	CLAY OR SHALE	SILT OR SILTSTONE	UNDISTURBED SAMPLE	DISTURBED SAMPLE

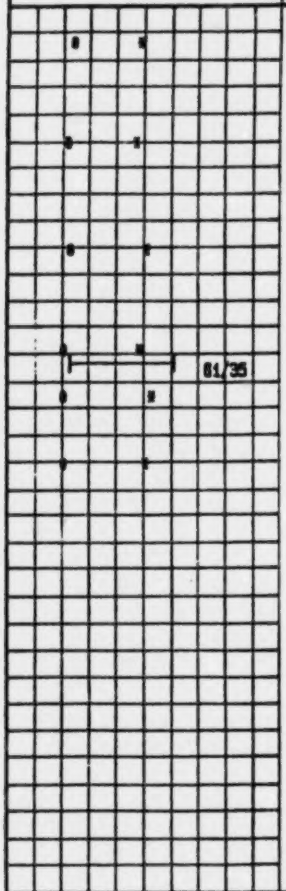
θ-MOISTURE CONTENT (%), ⊠-WET UNIT WEIGHT (kg/m³), K-PERMEABILITY (cm/s), F.A.-FLIGHT AUGER, HCA-HOLLOW CORE AUGER, T OR S.P.T.-STANDARD PENETRATION TEST BLOW COUNT,
P.P.-POCKET PENETROMETER (kPa), Qu – UNCONFINED COMPRESSION (kPa)
W_p -PLASTIC LIMIT (%) ├──┤ W_L -LIQUID LIMIT (%), ---- CORE RECOVERY (%),
12-0.03-22 – 12 = % RETAINED ON No.4 SIEVE, 0.03 = D_{10} SIZE mm, 22 = % No.200 SIEVE,
$\frac{40}{38} = \frac{\%\ SILT}{\%\ CLAY}$, ∇ – WATER LEVEL 2 DAYS AFTER DRILLING.

Alberta
ENVIRONMENT
DEVELOPMENT & OPERATIONS DIVISION
GEOTECHNICAL SERVICES LABORATORY

PROJECT EDGERTON SLIDE
SITE
HOLE No. ES 1 ELEV.
LOCATION
TECHNOLOGIST AS LX DATE DRILLED 26 Feb 1991

BOREHOLE AND TEST LOG

TEST RESULTS



DEPTH (m)	SYMBOL	DESCRIPTION	SAMPLE	OTHER INFORMATION
7	▨	as above, gyp lenses & crystals.	⧄	PP= 383+ Rec= .30m/.40m
	▨	as above, gyp lenses & crystals.	⧄	PP= 383+ Rec= .31m/.40m
8 ▽	▨			
	▨	as above, med-dk gry, gyp lenses & crystals, MS lenses & layers.	⧄	PP= 383+ Rec= .39m/.45m
9	▨	as above, mtld med-dk gry, gyp crystals, MS lenses & layers.	⧄	PP= 383+ Rec= .20m/.20m Began coring @ 9.5m with CB19 core barrel.
	▨	as above, interbedded med gry & dk gry, interbedded SS & MS layers, hard, badly frac, vert & diag frac.	⧄	Rec= 1.10m/1.10m
10	▨			
				Drilled to 35.0m with rockbit.
11				
12				
13				

●
20 40 60 80 100
■
1600 1800 2000 2200 2400

DEPTH SCALE
1 2 m
2 4 6 ft.

☐ TOPSOIL OR NO SAMPLE
▩ GRAVEL
▦ SAND OR SANDSTONE
▨ CLAY OR SHALE
▥ SILT OR SILTSTONE
⧄ UNDISTURBED SAMPLE
☒ DISTURBED SAMPLE

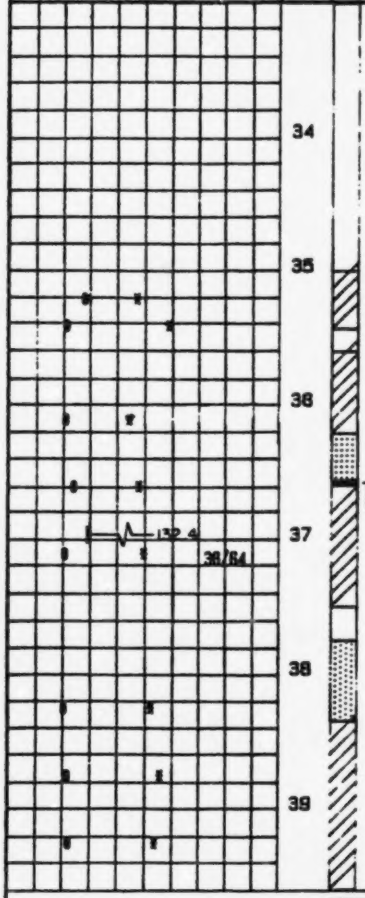
● - MOISTURE CONTENT (%), ■ - WET UNIT WEIGHT (kg/m^3), K - PERMEABILITY (cm/s), F.A. - FLIGHT AUGER,
HCA - HOLLOW CORE AUGER, N OR S.P.T. - STANDARD PENETRATION TEST BLOW COUNT,
P.P. - POCKET PENETROMETER (kPa), Qu - UNCONFINED COMPRESSION (kPa)
W_p - PLASTIC LIMIT (%) ├──┤ W_L - LIQUID LIMIT (%), - - - - CORE RECOVERY (%),
12-0.03-22 - 12 = % RETAINED ON No.4 SIEVE, 0.03 = D_{10} SIZE mm, 22 = % No.200 SIEVE,
$\frac{40}{38} = \frac{\%\ SILT}{\%\ CLAY}$, ▽ - WATER LEVEL

Alberta
ENVIRONMENT
DEVELOPMENT & OPERATIONS DIVISION
GEOTECHNICAL SERVICES LABORATORY

PROJECT EDGERTON SLIDE
SITE
HOLE No. ES 1 ELEV.
LOCATION
TECHNOLOGIST AS LK DATE DRILLED 26 Feb 1991

BOREHOLE AND TEST LOG

TEST RESULTS | DEPTH (m) | SYMBOL | DESCRIPTION | SAMPLE | OTHER INFORMATION



CLAYSTONE-hard, dk br gry, silt & sand lenses, shell frags, badly frac, vert & diag frac.
as above.

SANDSTONE-med-dk blue gry, f g, cl'y, interbedded CS & thin coal layers, shell frags, intact.
COAL-blk, hard.
CLAYSTONE-hard, dk br gry, occ tan layers, thin interbedded SS layers, shells, badly frac, vert & diag frac, occ small slicks.

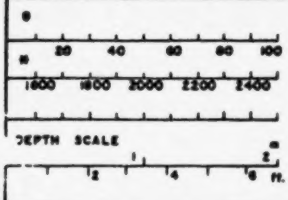
SANDSTONE-hard, med br gry, f g, cl'y, coal bands, interbedded CS layers @ 160-210mm, 280-400mm, badly frac
CLAYSTONE-med br gry, sandy, silty, interbedded SS layers shell frags & lenses @ 1360-1500mm, coal frags, badly frac, vert & diag frac.

Began coring @ 35.0m with CB19 core barrel.

Rec= .43m/.60m

Rec= 1.90m/2.15m

Rec= 2.97m/3.00m



▭ TOPSOIL OR NO SAMPLE
▩ GRAVEL
▒ SAND OR SANDSTONE
▨ CLAY OR SHALE
▥ SILT OR SILTSTONE
◩ UNDISTURBED SAMPLE
☒ DISTURBED SAMPLE

●-MOISTURE CONTENT (%), ⊕-WET UNIT WEIGHT (kg/m^3), K-PERMEABILITY (cm/s), F.A.-FLIGHT AUGER, HCA-HOLLOW CORE AUGER, ▼ OR S.P.T.-STANDARD PENETRATION TEST BLOW COUNT, P.P.-POCKET PENETROMETER (kPa), Qu-UNCONFINED COMPRESSION (kPa)
W_p-PLASTIC LIMIT (%) ⊢—⊣ W_L-LIQUID LIMIT (%), ---- CORE RECOVERY (%),
12-0.03-22 - 12 = % RETAINED ON No.4 SIEVE, 0.03 = D_{10} SIZE mm, 22 = % No.200 SIEVE,
$\frac{40}{36} = \frac{\% \text{SILT}}{\% \text{CLAY}}$, ∇-WATER LEVEL

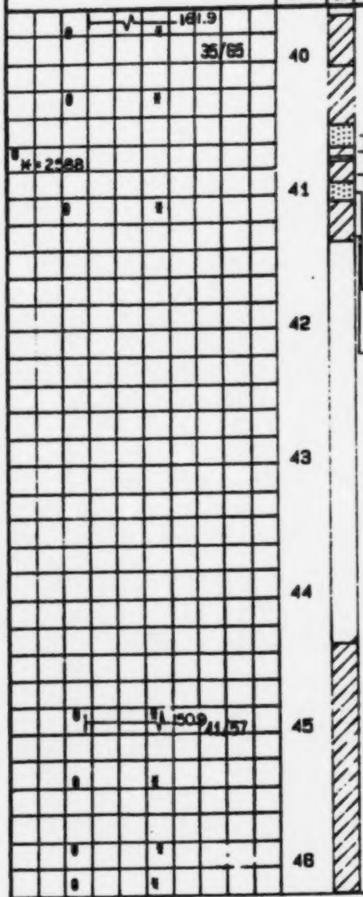
GS-04-86

Alberta ENVIRONMENT
DEVELOPMENT & OPERATIONS DIVISION
GEOTECHNICAL SERVICES LABORATORY

PROJECT EDGERTON SLIDE
SITE
HOLE No. ES 1 ELEV.
LOCATION
TECHNOLOGIST AS LK DATE DRILLED 26 Feb 1991

BOREHOLE AND TEST LOG

TEST RESULTS	DEPTH (m)	SYMBOL	DESCRIPTION	SAMPLE	OTHER INFORMATION



CLAYSTONE-hard, dk br gry, badly frac, vert & diag frac

CLAYSTONE-hard, interbedded med blue gry & dk gry, interbedded SS layers, bedding @ approx. 8 degrees to horizontal, badly frac.

SANDSTONE-v hard, lt gry, cal, shell frags, badly frac

CLAYSTONE-dk gry, hard, remolded, shell frags, small slicks.

CLAYSTONE-hard, dk br gry, interbedded med blue gry SS layers, v thin coal seams.

SANDSTONE-hard, med blue gry interbedded dk br gry CS layers, v thin coal seams, f g, cl'y.

CLAYSTONE-hard, dk br gry, remolded @ 360-520mm, SS lenses, vert & diag fract.

Rec= .60m/3.00m

CLAYSTONE-hard, dk gry br with occ lam layers & nodules, badly frac, diag & vert frac, thin interbedded med gry SS layers @ 330-1040mm & 1775-1840mm, shell frags, remolded @ 0-200mm, small slicks @ 1900-1950mm.

Rec= 1.95m/2.45m

●
20 40 60 80 100
⊕
1600 1800 2000 2200 2400

DEPTH SCALE 1 2 m
2 4 6 ft.

☐ TOPSOIL OR NO SAMPLE
▩ GRAVEL
▦ SAND OR SANDSTONE
▨ CLAY OR SHALE
▥ SILT OR SILTSTONE
◿ UNDISTURBED SAMPLE
☒ DISTURBED SAMPLE

● - MOISTURE CONTENT (%), ⊕ - WET UNIT WEIGHT (kg/m³), K - PERMEABILITY (cm/s), F.A. - FLIGHT AUGER, HCA - HOLLOW CORE AUGER, V OR S.P.T. - STANDARD PENETRATION TEST BLOW COUNT, P.P. - POCKET PENETROMETER (kPa), Qu - UNCONFINED COMPRESSION (kPa)
W_p - PLASTIC LIMIT (%) ├──┤ W_L - LIQUID LIMIT (%), - - - - CORE RECOVERY (%),
12-0.03-22 - 12 = % RETAINED ON No.4 SIEVE, 0.03 = D_{10} SIZE mm, 22 = % No.200 SIEVE,
$\frac{40}{35} = \frac{\%\ SILT}{\%\ CLAY}$, ∇ - WATER LEVEL

Alberta
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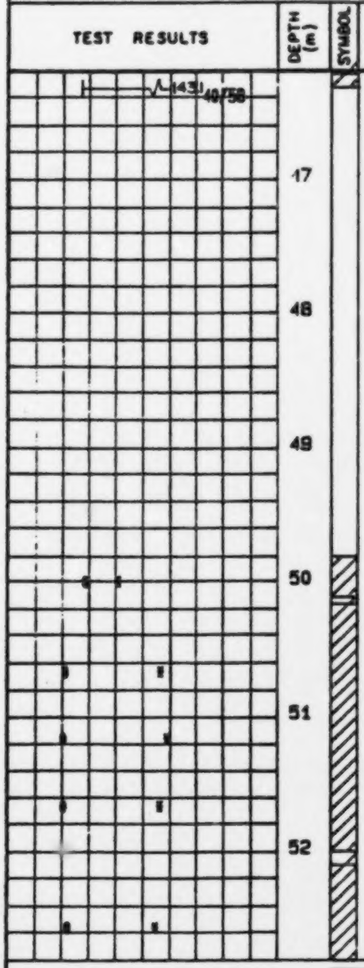
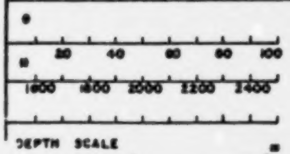
DEVELOPMENT & OPERATIONS DIVISION
GEOTECHNICAL SERVICES LABORATORY

PROJECT EDGERTON SLIDE
SITE
HOLE No. ES 1 ELEV.
LOCATION
TECHNOLOGIST AS LK DATE DRILLED 26 Feb 1991

BOREHOLE AND TEST LOG



DESCRIPTION	OTHER INFORMATION
CLAYSTONE-hard, dk br gry, remolded, heavily slick'd.	Rec= .30m/.35m
CLAYSTONE-hard, dk br gry, interbedded gry SS & MS layers, badly frac, vert & diag frac, infilled fractures.	Rec= 1.84m/2.75m



☐ TOPSOIL OR NO SAMPLE ▩ GRAVEL ▦ SAND OR SANDSTONE ▨ CLAY OR SHALE ▥ SILT OR SILTSTONE ◸ UNDISTURBED SAMPLE ☒ DISTURBED SAMPLE

● - MOISTURE CONTENT (%), ■ - WET UNIT WEIGHT (kg/m³), K - PERMEABILITY (cm/s), F.A. - FLIGHT AUGER, HCA - HOLLOW CORE AUGER, ▼ OR S.P.T. - STANDARD PENETRATION TEST BLOW COUNT, P.P. - POCKET PENETROMETER (kPa), Qu - UNCONFINED COMPRESSION (kPa) W_p - PLASTIC LIMIT (%) ├──┤ W_L - LIQUID LIMIT (%), - - - - CORE RECOVERY (%), 12-0.03-22 - 12 = % RETAINED ON No.4 SIEVE, 0.03 = D_{10} SIZE mm, 22 = % No.200 SIEVE, $\frac{40}{58} = \frac{\%\ SILT}{\%\ CLAY}$, ▽ - WATER LEVEL

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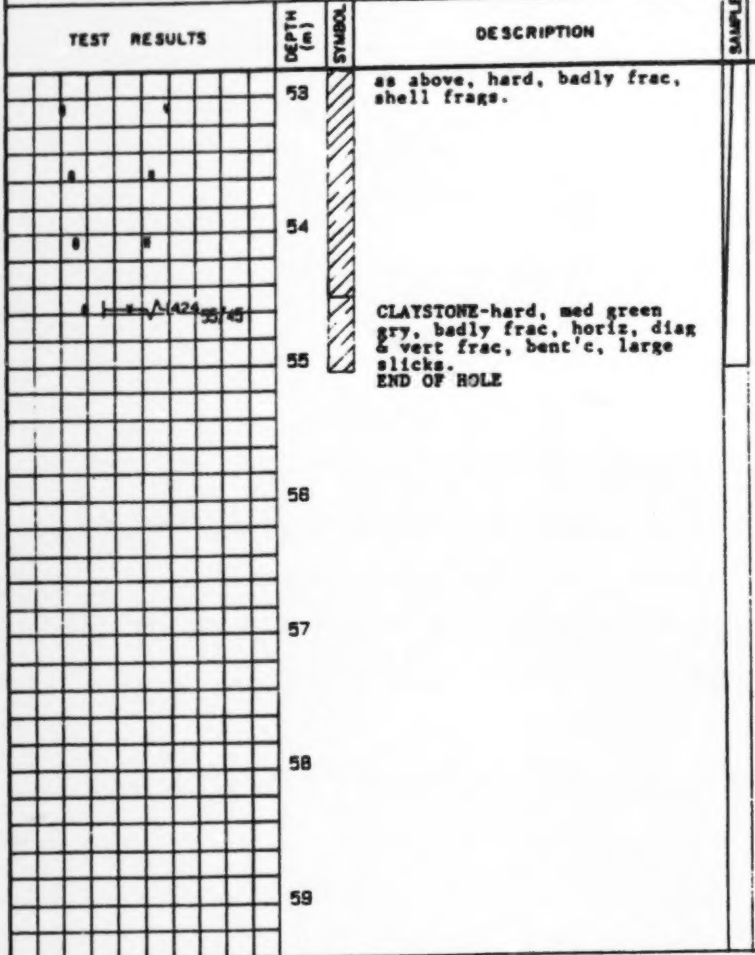
DEVELOPMENT & OPERATIONS DIVISION
GEOTECHNICAL SERVICES LABORATORY

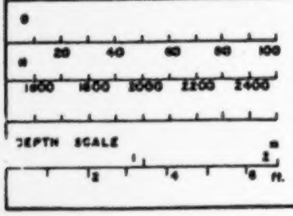
PROJECT EDGERTON SLIDE
SITE
HOLE No. ES 1 ELEV.
LOCATION
TECHNOLOGIST AS LK DATE DRILLED 26 Feb 1991

BOREHOLE AND TEST LOG



DEPTH (m)	DESCRIPTION	OTHER INFORMATION
53	as above, hard, badly frac, shell frags.	Rec= 2.96m/2.15m
55	CLAYSTONE-hard, med green gry, badly frac, horiz, diag & vert frac, bent'c, large slicks. END OF HOLE	

☐	▩	▦	▨	▥	◪	☒
TOPSOIL OR NO SAMPLE	GRAVEL	SAND OR SANDSTONE	CLAY OR SHALE	SILT OR SILTSTONE	UNDISTURBED SAMPLE	DISTURBED SAMPLE



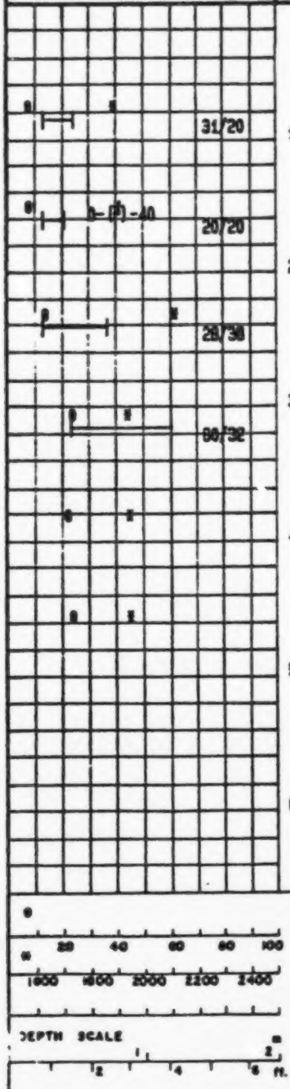
θ-MOISTURE CONTENT (%), γ-WET UNIT WEIGHT (kg/m³), K-PERMEABILITY (cm/s), F.A.-FLIGHT AUGER, HCA-HOLLOW CORE AUGER, ▼ OR S.P.T.-STANDARD PENETRATION TEST BLOW COUNT,
P.P.-POCKET PENETROMETER (kPa), Qu - UNCONFINED COMPRESSION (kPa)
W_p -PLASTIC LIMIT (%) ├──┤ W_L -LIQUID LIMIT (%), ---- CORE RECOVERY (%),
12-0.03-22 - 12 = % RETAINED ON No.4 SIEVE, 0.03 = D_{10} SIZE mm, 22 = % No.200 SIEVE,
$\frac{40}{38} = \frac{\%\ SILT}{\%\ CLAY}$, ∇- WATER LEVEL

Alberta ENVIRONMENT
DEVELOPMENT & OPERATIONS DIVISION
GEOTECHNICAL SERVICES LABORATORY

PROJECT EDGERTON SLIDE
SITE
HOLE No. ES 2 ELEV.
LOCATION
TECHNOLOGIST AS LK DATE DRILLED 4 Mar 1991

BOREHOLE AND TEST LOG

TEST RESULTS



DEPTH (m)	SYMBOL	DESCRIPTION	SAMPLE	OTHER INFORMATION
	▨			RIG: MOBILE B-61S AUGER TYPE: 203mm HCA
1	▨	CL(TILL)-hard, med br, roots coal & CS chips, rust spots, cal, fissures.	◺	PP= 383+ Rec= .27m/.30m
2	▒	SC-med br, f g, coal spots, till pkts.	◺	PP= (-) Rec= .20m/.40m
	▨	CI(TILL)-hard, dk br, coal & CS chips, odd pebble, gyp crystals, SM pkt @ 200-250mm	◺	PP= 383+ Rec= .28m/.30m
3	▨	CLAYSTONE-hard, dk br, MS & SS lenses, rust coated frac, gyp crystals.	◺	PP= 383+ Rec= .27m/.45m
4	▨	as above.	◺	PP= 383+ Rec= .25m/.45m
5	▨	as above.	◺	PP= 383+ Rec= .36m/.40m
6				

☐	▦	▒	▨	▥	◺	☒
TOPSOIL OR NO SAMPLE	GRAVEL	SAND OR SANDSTONE	CLAY OR SHALE	SILT OR SILTSTONE	UNDISTURBED SAMPLE	DISTURBED SAMPLE

θ-MOISTURE CONTENT (%), W-WET UNIT WEIGHT (kg/m^3), K-PERMEABILITY (cm/s), F.A.-FLIGHT AUGER, HCA-HOLLOW CORE AUGER, T OR S.P.T.-STANDARD PENETRATION TEST BLOW COUNT, P.P.-POCKET PENETROMETER (kPa), Qu-UNCONFINED COMPRESSION (kPa)
W_p-PLASTIC LIMIT (%) ├──┤ W_L-LIQUID LIMIT (%), ---- CORE RECOVERY (%),
12-0.03-22 - 12 = % RETAINED ON No.4 SIEVE, 0.03 = D_{10} SIZE mm, 22 = % No.200 SIEVE,
$\frac{40}{38} = \frac{\%\ SILT}{\%\ CLAY}$. ∇- WATER LEVEL NOT TAKEN.

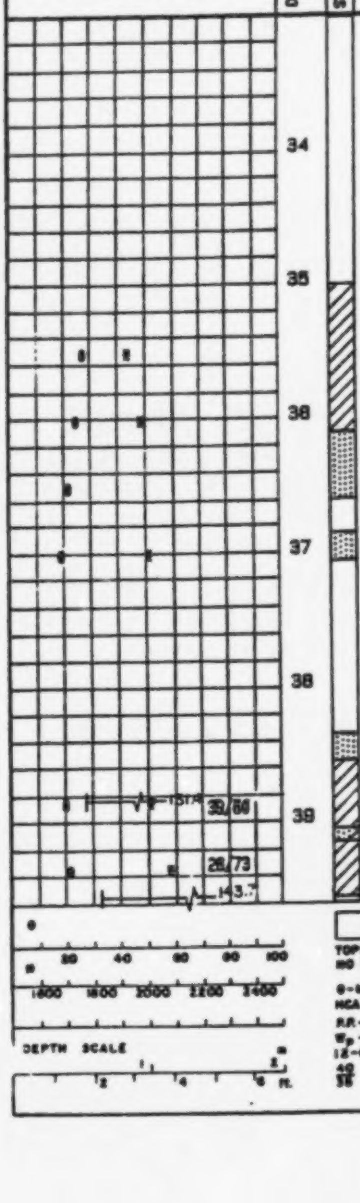
GS-04-86

Alberta
ENVIRONMENT
DEVELOPMENT & OPERATIONS DIVISION
GEOTECHNICAL SERVICES LABORATORY

PROJECT EDGERTON SLIDE
SITE
HOLE No. ES 2 ELEV.
LOCATION
TECHNOLOGIST AS LX DATE DRILLED 4 Mar 1991

BOREHOLE AND TEST LOG

TEST RESULTS | DEPTH (m) | SYMBOL | DESCRIPTION | SAMPLE | OTHER INFORMATION



CLAYSTONE-hard, dk gry, mod frac, vert frac @ 520-700mm, interbedded thin carb, MS & SS layers, ironstone nodules @ 930mm.

Rec= 1.60m/1.85m

SANDSTONE-hard, dk gry, to med br @ 1410mm, soft & badly vweath @ 1410-1600mm, f g ironstone nodules.

as above, soft, clay layer @ 0-30mm, badly weath.
as above, stiff, weath, med gry, interbedded coal layers v hard @ 110mm.

Rec= .11m/1.40m

as above, hard, lt gry, cal, coal lenses.
CLAYSTONE-hard, dk gry, interbedded SS layers, vert & diag fracs, remolded @ 530-580mm.
SANDSTONE-hard, med gry, cl'y, sh frags, coal lenses & layers.
CLAYSTONE-hard, dk gry, inter-

Rec= 1.21m/1.50m

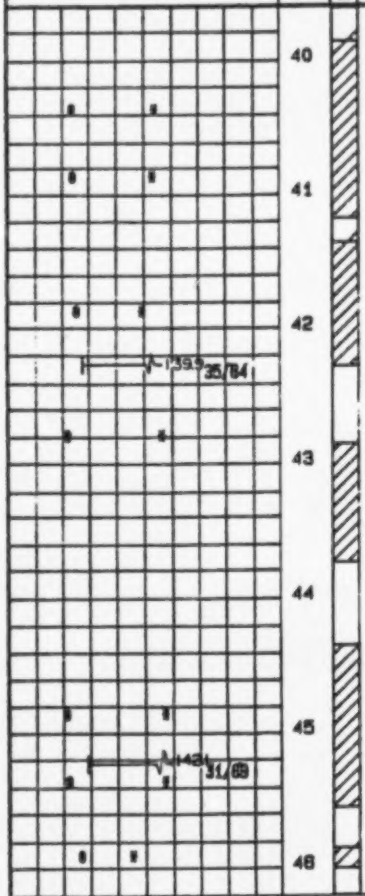
☐	▩	▦	▨	▥	◩	☒
TOPSOIL OR NO SAMPLE	GRAVEL	SAND OR SANDSTONE	CLAY OR SHALE	SILT OR SILTSTONE	UNDISTURBED SAMPLE	DISTURBED SAMPLE

● - MOISTURE CONTENT (%), ■ - WET UNIT WEIGHT (kg/m^3), K - PERMEABILITY (cm/s), F.A. - FLIGHT AUGER, HCA - HOLLOW CORE AUGER, V OR S.P.T. - STANDARD PENETRATION TEST BLOW COUNT, P.P. - POCKET PENETROMETER (kPa), Qu - UNCONFINED COMPRESSION (kPa)
W_p - PLASTIC LIMIT (%) ├──┤ W_L - LIQUID LIMIT (%), - - - - CORE RECOVERY (%),
12-0.03-22 - 12 = % RETAINED ON No.4 SIEVE, 0.03 = D_{10} SIZE mm, 22 = % No.200 SIEVE,
$\frac{40}{38} = \frac{\%\ SILT}{\%\ CLAY}$, ∇ - WATER LEVEL

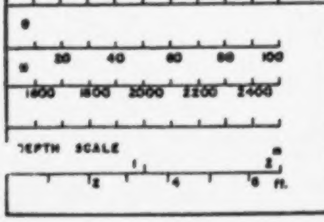
Alberta
ENVIRONMENT
DEVELOPMENT & OPERATIONS DIVISION
GEOTECHNICAL SERVICES LABORATORY

PROJECT EDGERTON SLIDE
SITE
HOLE No. ES 2 ELEV.
LOCATION
TECHNOLOGIST AS LK DATE DRILLED 4 Mar 1991

BOREHOLE AND TEST LOG



DESCRIPTION	OTHER INFORMATION
bedded SS layer @ 1040-1080mm, badly frac, vert & diag frac, slicks @ approx. 60% to horiz.	
as above, interbedded tan layers, mod frac, interbedded thin coal, SS & MS layers, bedding inclined @ approx. 5 degrees, mod frac, vert & diag frac.	Rec= 1.32m/1.50m
as above, interbedded tan layers @ 0-440mm, interbedded SS layers, shell frags, mod frac, vert & diag frac, slicks @ 800-910mm.	Rec= .92m/1.50m
as above, badly frac, vert & diag frac, remolded @ 0-220mm, shell frags.	Rec= .88m/1.50m
as above, interbedded med blue gry & dk gry, bedding inclined @ approx. 5-7 degrees, remolded @ 120-240mm, tan layers, slicks @ 770-880mm, shell frags.	Rec= 1.20m/1.50m
as above, hard, remolded @ 70-150mm, dk br gry, vert &	Rec= .15m/1.50m



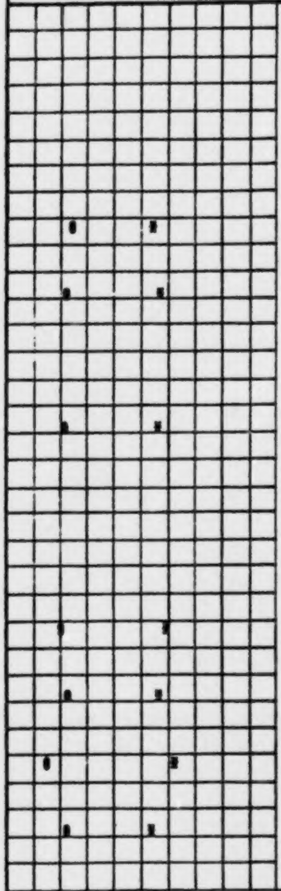
☐	▩	▦	▨	▥	◩	☒
TOPSOIL OR NO SAMPLE	GRAVEL	SAND OR SANDSTONE	CLAY OR SHALE	SILT OR SILTSTONE	UNDISTURBED SAMPLE	DISTURBED SAMPLE

θ - MOISTURE CONTENT (%), Φ - WET UNIT WEIGHT (kg/m^3), K - PERMEABILITY (cm/s), F.A. - FLIGHT AUGER, HCA - HOLLOW CORE AUGER, ∇ OR S.P.T. - STANDARD PENETRATION TEST BLOW COUNT, P.P. - POCKET PENETROMETER (kPa), Qu - UNCONFINED COMPRESSION (kPa)
W_p - PLASTIC LIMIT (%) ├── W_L - LIQUID LIMIT (%), - - - - CORE RECOVERY (%),
12-0.03-22 - 12 = % RETAINED ON No.4 SIEVE, 0.03 = D_{10} SIZE mm, 22 = % No.200 SIEVE,
$\frac{40}{35} = \frac{\%\ SILT}{\%\ CLAY}$, ∇ - WATER LEVEL

Alberta
ENVIRONMENT
DEVELOPMENT & OPERATIONS DIVISION
GEOTECHNICAL SERVICES LABORATORY

PROJECT EDGERTON SLIDE
SITE
HOLE No. ES 2 ELEV.
LOCATION
TECHNOLOGIST AS LK DATE DRILLED 4 Mar 1991

BOREHOLE AND TEST LOG



DEPTH (m)	SYMBOL	DESCRIPTION	OTHER INFORMATION
		diag frac.	
47			
	▨	as above, interbedded thin SS & ML layers, interbedded med gry & dk br gry, hard, vert frac @ 110-290mm, mod frac, infilled frac.	Rec= 1.34m/1.50m
48	▨		
49	▨	as above, hard, shell frags, remolded @ 260-340mm, 380-430mm & 540-690mm, vert & diag frac, interbedded SS & MS layers, infilled frac, interbedded med gry-dk gry.	Rec= .74m/1.50m
50			
	▨	as above, hard, interbedded med gry & dk br gry, interbedded SS & MS layers, mod frac, vert & diag fracs, remolded @ 0-220mm, 1160-1240mm & 1420-1480mm.	Rec= 1.50m/1.50m
51	▨		
52	▨	as above, hard, interbedded SS & MS lenses & layers, interbedded med gry & dk br gry, badly-mod frac, vert & diag frac, sl'ty remolded @ 0-80mm, shell frags.	Rec= .76m/1.50m

●
w 20 40 60 80 100
1600 1800 2000 2200 2400
DEPTH SCALE m 1 2
2 4 6 ft.

☐ TOPSOIL OR NO SAMPLE ▩ GRAVEL ▦ SAND OR SANDSTONE ▨ CLAY OR SHALE ▥ SILT OR SILTSTONE ◿ UNDISTURBED SAMPLE ☒ DISTURBED SAMPLE

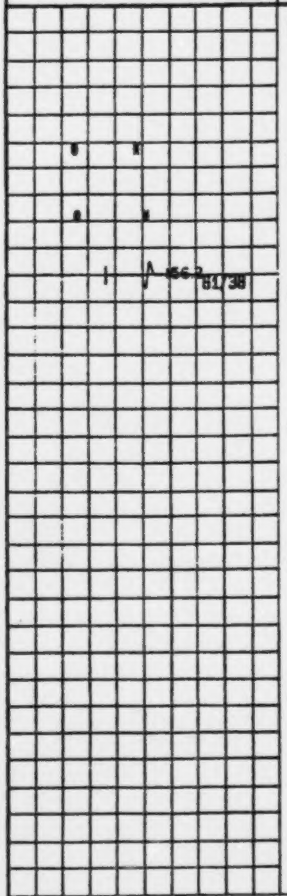
● - MOISTURE CONTENT (%), ● - WET UNIT WEIGHT (kg/m^3), K - PERMEABILITY (cm/s), F.A. - FLIGHT AUGER, HCA - HOLLOW CORE AUGER, V OR S.P.T. - STANDARD PENETRATION TEST BLOW COUNT, P.P. - POCKET PENETROMETER (kPa), Qu - UNCONFINED COMPRESSION (kPa) W_p - PLASTIC LIMIT (%) ├──┤ W_L - LIQUID LIMIT (%), ---- CORE RECOVERY (%), 12-0.03-22 - 12 = % RETAINED ON No.4 SIEVE, 0.03 = D_{10} SIZE mm, 22 = % No.200 SIEVE, $\frac{40}{38} = \frac{\%\ SILT}{\%\ CLAY}$, $\underline{\nabla}$ - WATER LEVEL

Alberta
ENVIRONMENT
DEVELOPMENT & OPERATIONS DIVISION
GEOTECHNICAL SERVICES LABORATORY

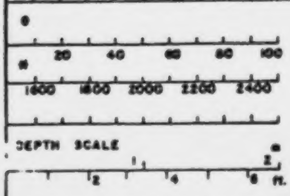
PROJECT EDGERTON SLIDE
SITE
HOLE No. ES 2 ELEV.
LOCATION
TECHNOLOGIST AS LK DATE DRILLED 4 Mar 1991

BOREHOLE AND TEST LOG

TEST RESULTS



DEPTH (m)	SYMBOL	DESCRIPTION	SAMPLE	OTHER INFORMATION
53	☐			
	▨	as above, interbedded SS & MS layers, badly frac, vert & diag frac, interbedded med gry-dk gry br, possibly bent'c @ 1240-1440mm, re-molded @ 0-300mm, large slicks @ 1060-1440mm @ approx. 35 degrees to horiz.		Rec= 1.44m/2.15m
54	▨			
55	☐	END OF HOLE		
56				
57				
58				
59				



☐ TOPSOIL OR NO SAMPLE ▩ GRAVEL ▦ SAND OR SANDSTONE ▨ CLAY OR SHALE ▥ SILT OR SILTSTONE ◪ UNDISTURBED SAMPLE ☒ DISTURBED SAMPLE

θ - MOISTURE CONTENT (%), γ - WET UNIT WEIGHT (kg/m³), K - PERMEABILITY (cm/s), F.A. - FLIGHT AUGER, HCA - HOLLOW CORE AUGER, N OR S.P.T. - STANDARD PENETRATION TEST BLOW COUNT, P.P. - POCKET PENETROMETER (kPa), Qu - UNCONFINED COMPRESSION (kPa) W_p - PLASTIC LIMIT (%) ⊢—⊣ W_L - LIQUID LIMIT (%), ---- CORE RECOVERY (%), 12-0.03-22 - 12 = % RETAINED ON No.4 SIEVE, 0.03 = D_{10} SIZE mm, 22 = % No.200 SIEVE, $\frac{40}{38} = \frac{\%\ SILT}{\%\ CLAY}$, ∇ - WATER LEVEL

GS-104-86

Alberta
ENVIRONMENT
DEVELOPMENT & OPERATIONS DIVISION
GEOTECHNICAL SERVICES LABORATORY

PROJECT EDGERTON SLIDE
SITE
HOLE No. ES 2A ELEV.
LOCATION
TECHNOLOGIST AS LK DATE DRILLED 7 Mar 1991

BOREHOLE AND TEST LOG

TEST RESULTS	DEPTH (m)	SYMBOL	DESCRIPTION	SAMPLE	OTHER INFORMATION
			No descriptions available from 0.00-36.3m.		RIG: MOBILE B-61S AUGER TYPE: 203mm HCA Rotary drill to 36.3m witH wing bit.
	1				
	2				
	3				
	4				
	5				
	6				

θ
20 40 60 80 100
γ
1600 1800 2000 2200 2400

DEPTH SCALE m 1 2
2 4 6 ft.

☐	▩	▦	▨	▥	⧄	☒
TOPSOIL OR NO SAMPLE	GRAVEL	SAND OR SANDSTONE	CLAY OR SHALE	SILT OR SILTSTONE	UNDISTURBED SAMPLE	DISTURBED SAMPLE

θ - MOISTURE CONTENT (%), γ - WET UNIT WEIGHT (kg/m^3), K - PERMEABILITY (cm/s), F.A. - FLIGHT AUGER, HCA - HOLLOW CORE AUGER, N OR S.P.T. - STANDARD PENETRATION TEST BLOW COUNT, P.P. - POCKET PENETROMETER (kPa), Qu - UNCONFINED COMPRESSION (kPa)
W_P - PLASTIC LIMIT (%) |——| W_L - LIQUID LIMIT (%), ---- CORE RECOVERY (%),
12-0.05-22 - 12 = % RETAINED ON No.4 SIEVE, 0.05 = D_{10} SIZE mm, 22 = % No.200 SIEVE,
$\frac{40}{35} = \frac{\%\ \text{SILT}}{\%\ \text{CLAY}}$, ∇ - WATER LEVEL

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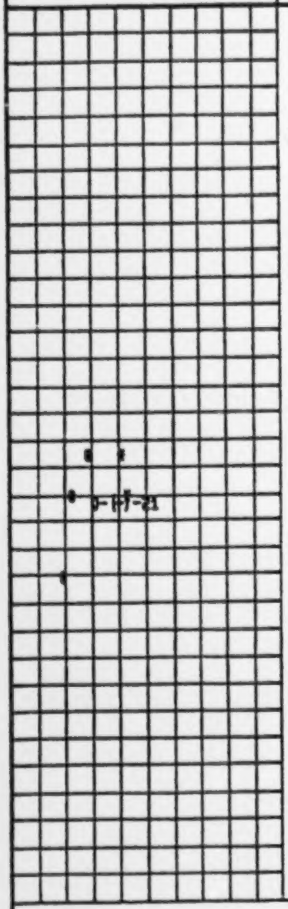
ENVIRONMENT
DEVELOPMENT & OPERATIONS DIVISION
GEOTECHNICAL SERVICES LABORATORY

PROJECT EDGERTON SLIDE
SITE
HOLE No. ES 2A ELEV.
LOCATION
TECHNOLOGIST AS LK DATE DRILLED 7 Mar 1991

BOREHOLE AND TEST LOG

TEST RESULTS



DEPTH (m)	SYMBOL	DESCRIPTION	SAMPLE	OTHER INFORMATION
34				
35				
36				
	▒	SANDSTONE-badly weath, med-lt br, f g, rust stained frac.	⧄	Rec= .12m/.30m
	▒	as above, badly weath.	⧄	Rec= .09m/.30m
37	▒			
	▒	as above.	⧄	Advanced hole to 37.8m.
	☐	END OF HOLE		
38				
39				

●
20 40 60 80 100
■
1600 1800 2000 2200 2400

DEPTH SCALE 1 2 m
2 4 6 ft.

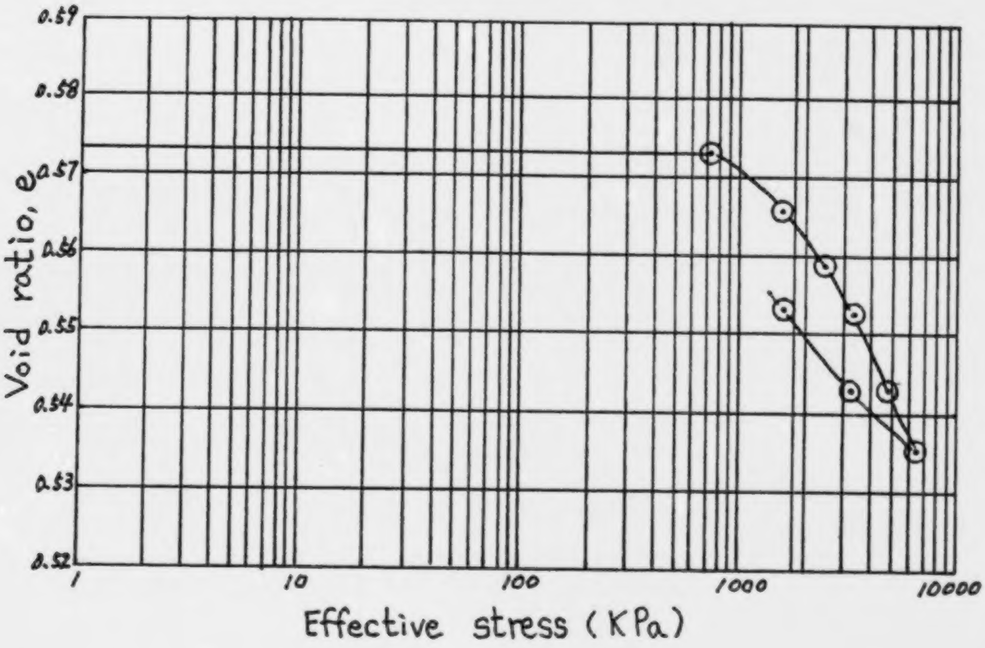
☐ TOPSOIL OR NO SAMPLE
▩ GRAVEL
▒ SAND OR SANDSTONE
▨ CLAY OR SHALE
▥ SILT OR SILTSTONE
⧄ UNDISTURBED SAMPLE
☒ DISTURBED SAMPLE

● - MOISTURE CONTENT (%), ■ - WET UNIT WEIGHT (kg/m^3), K - PERMEABILITY (cm/s), F.A. - FLIGHT AUGER,
HCA - HOLLOW CORE AUGER, N OR S.P.T. - STANDARD PENETRATION TEST BLOW COUNT,
P.P. - POCKET PENETROMETER (kPa), Qu - UNCONFINED COMPRESSION (kPa)
W_p - PLASTIC LIMIT (%) ├──┤ W_L - LIQUID LIMIT (%), - - - - CORE RECOVERY (%),
12-0.03-22 - 12 = % RETAINED ON No.4 SIEVE, 0.03 = D_{10} SIZE mm, 22 = % No.200 SIEVE,
$\frac{40}{38} = \frac{\% \text{ SILT}}{\% \text{ CLAY}}$, $\underline{\nabla}$ - WATER LEVEL

Appendix 4

Laboratory Tests Results

(a)



Soil Type: Claystone (ES-1; $38.^{34}$ – $38.^{41}$ m)

Liquid Limit: 107.1 % Plastic Limit: 23.7 % Plasticity Index: 83.3 %

Sand: 3 % Silt: 69 % Clay: 28 %

Initial Water Content: 19.65 % Saturation: 95.4 %

Final Water Content: 19.87 % Saturation: 100.0 %

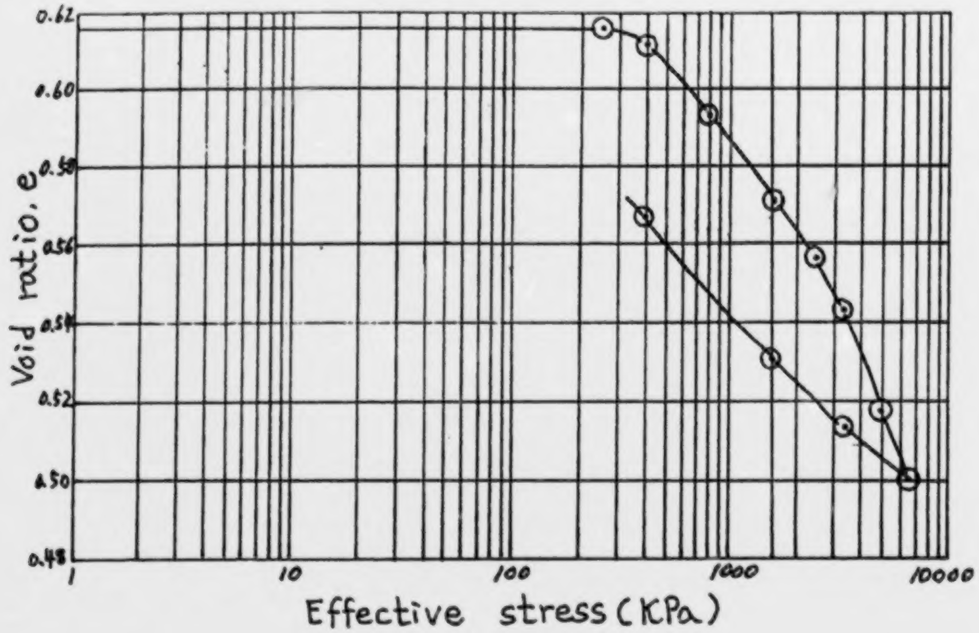
Swelling Pressure: 713 KPa

Compressive Index: 0.058

Preconsolidation Pressure: 1800 KPa

Figure A.1 Void ratio versus log effective stress curve

(b)



Soil Type: Claystone (ES-1; 44.^{89} – 45.^{01} m)

Liquid Limit: 142.7 % Plastic Limit: 27.9 % Plasticity Index: 114.8 %

Sand: 0 % Silt: 38 % Clay: 62 %

Initial Water Content: 22.5 % Saturation: 100.0 %

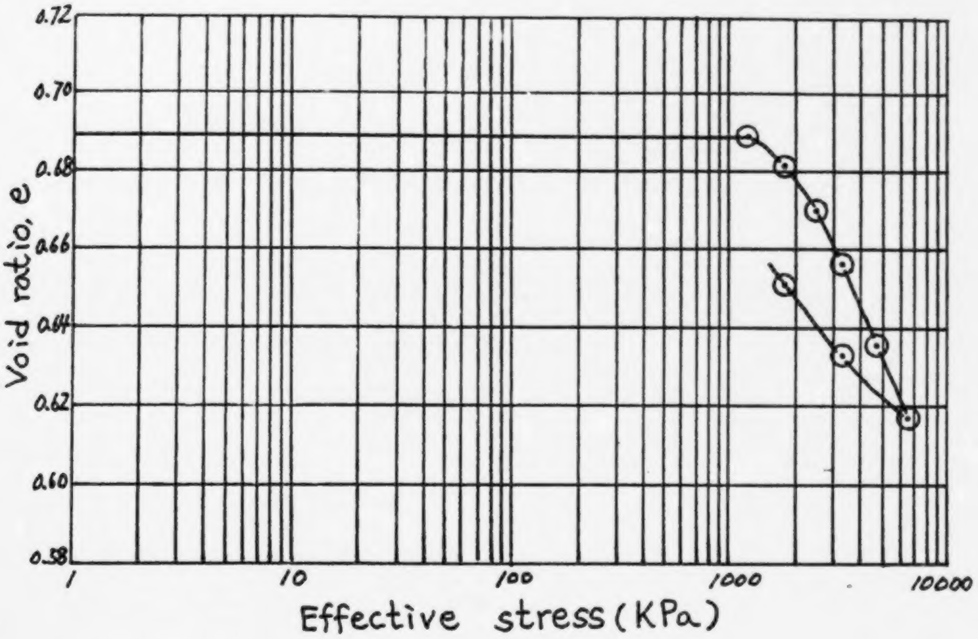
Final Water Content: 20.9 % Saturation: 100.0 %

Swelling Pressure: 252.1 KPa

Compressive Index: 0.146

Preconsolidation Pressure: 1600 KPa

(c)



Soil Type: Claystone (ES-1 ; 54.55 – 54.61 m)

Liquid Limit: 122.8 % Plastic Limit: 33.6 % Plasticity Index: 89.2 %

Sand: 3 % Silt: 60 % Clay: 37 %

Initial Water Content: 23.6 % Saturation: 94.3 %

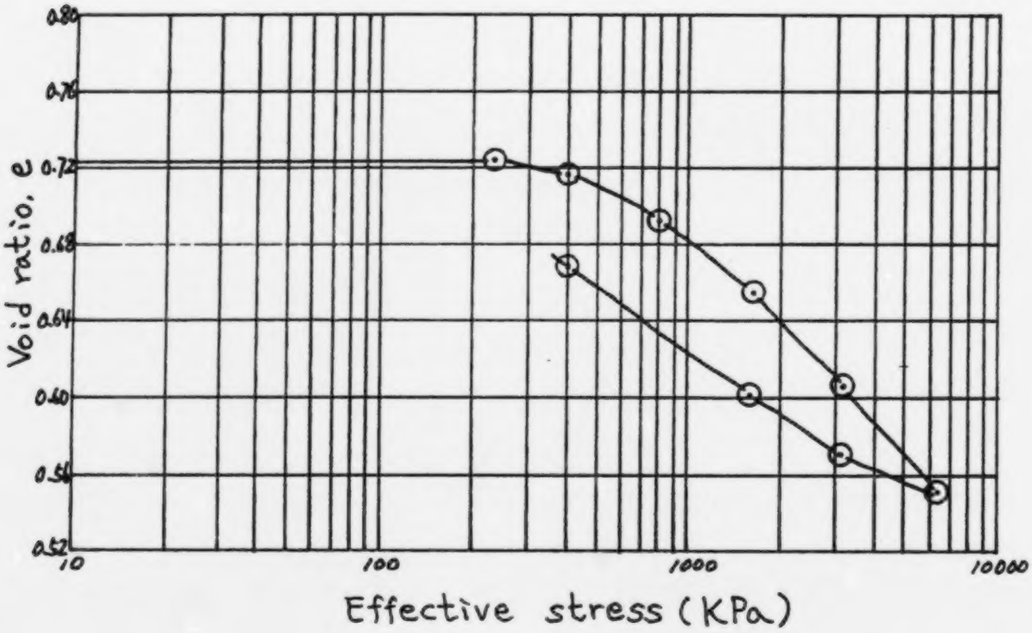
Final Water Content: 23.6 % Saturation: 100.0 %

Swelling Pressure: 1279 KPa

Compressive Index: 0.111

Preconsolidation Pressure: 2000 KPa

(d)



Soil Type: Claystone (ES-2 ; $35.^{25}$ – $35.^{30}$ m)

Liquid Limit: 105.9 % Plastic Limit: 29.0 % Plasticity Index: 76.8 %

Sand: % Silt: % Clay: %

Initial Water Content: 25.71 % Saturation: 96.3 %

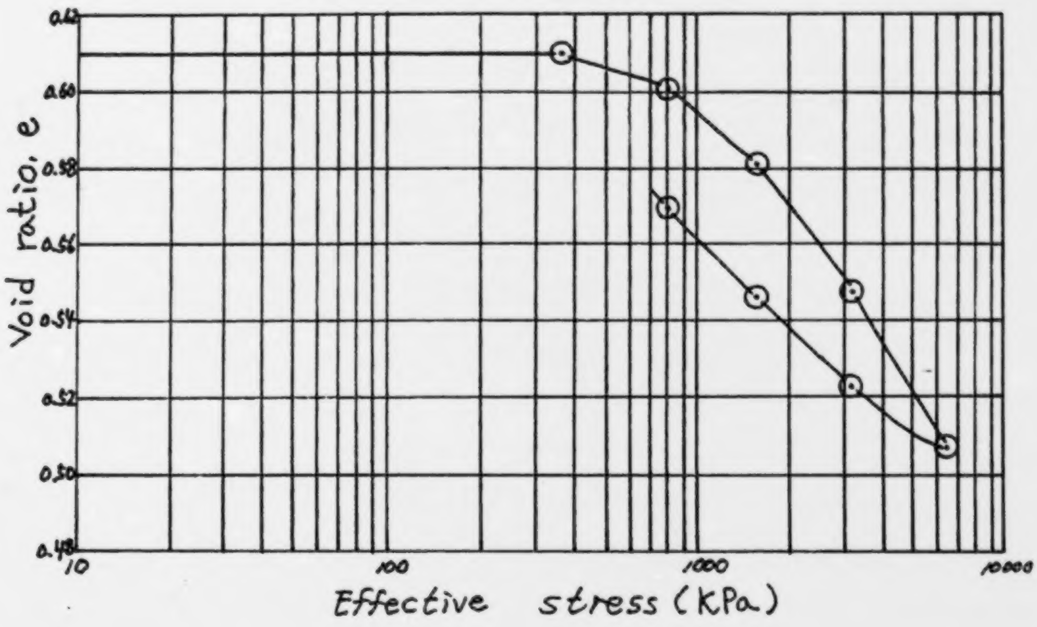
Final Water Content: 25.32 % Saturation: 100.0 %

Swelling Pressure: 231.2 KPa

Compressive Index: 0.169

Preconsolidation Pressure: 1000 KPa

(e)



Soil Type: Claystone (ES-2 ; $45.^{41}$ – $45.^{48}$ m)

Liquid Limit: 122.3 % Plastic Limit: 27.3 % Plasticity Index: 95.0 %

Sand: 0 % Silt: 40 % Clay: 60 %

Initial Water Content: 22.34 % Saturation: 95.3 %

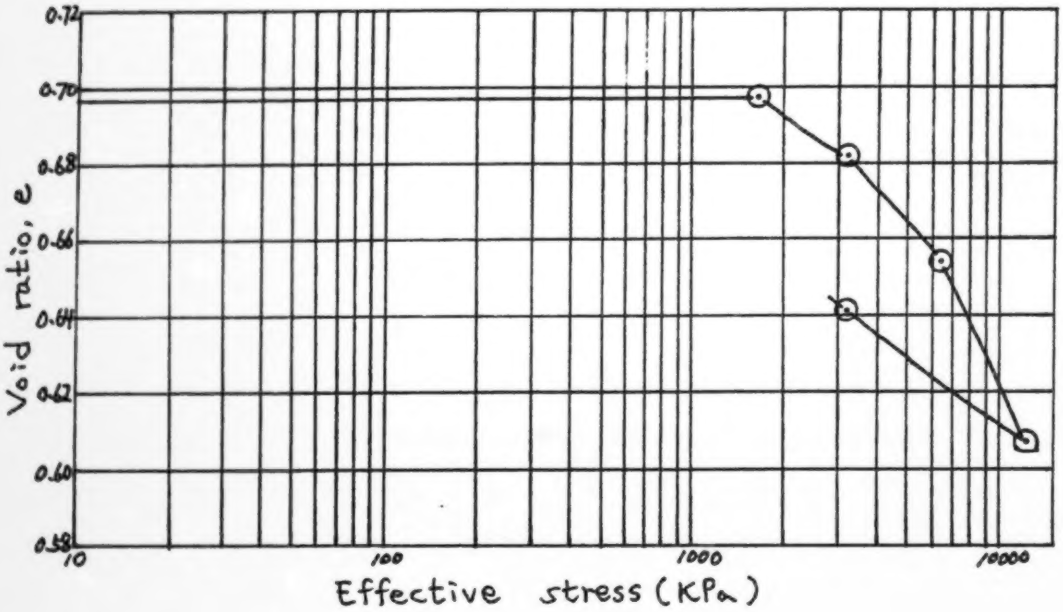
Final Water Content: 20.85 % Saturation: 100.0 %

Swelling Pressure: 359.1 KPa

Compressive Index: 0.121

Preconsolidation Pressure: 1800 KPa

(f)



Soil Type: Claystone (ES-2 ; 54.^{39} - 54.^{49} m)

Liquid Limit: 108.2 % Plastic Limit: 31.9 % Plasticity Index: 76.3 %

Sand: 0 % Silt: 69 % Clay: 31 %

Initial Water Content: 25.33 % Saturation: 99.3 %

Final Water Content: 24.73 % Saturation: 100.0 %

Swelling Pressure: 1066 KPa

Compressive Index: 0.122

Preconsolidation Pressure: 4100 KPa

(a)

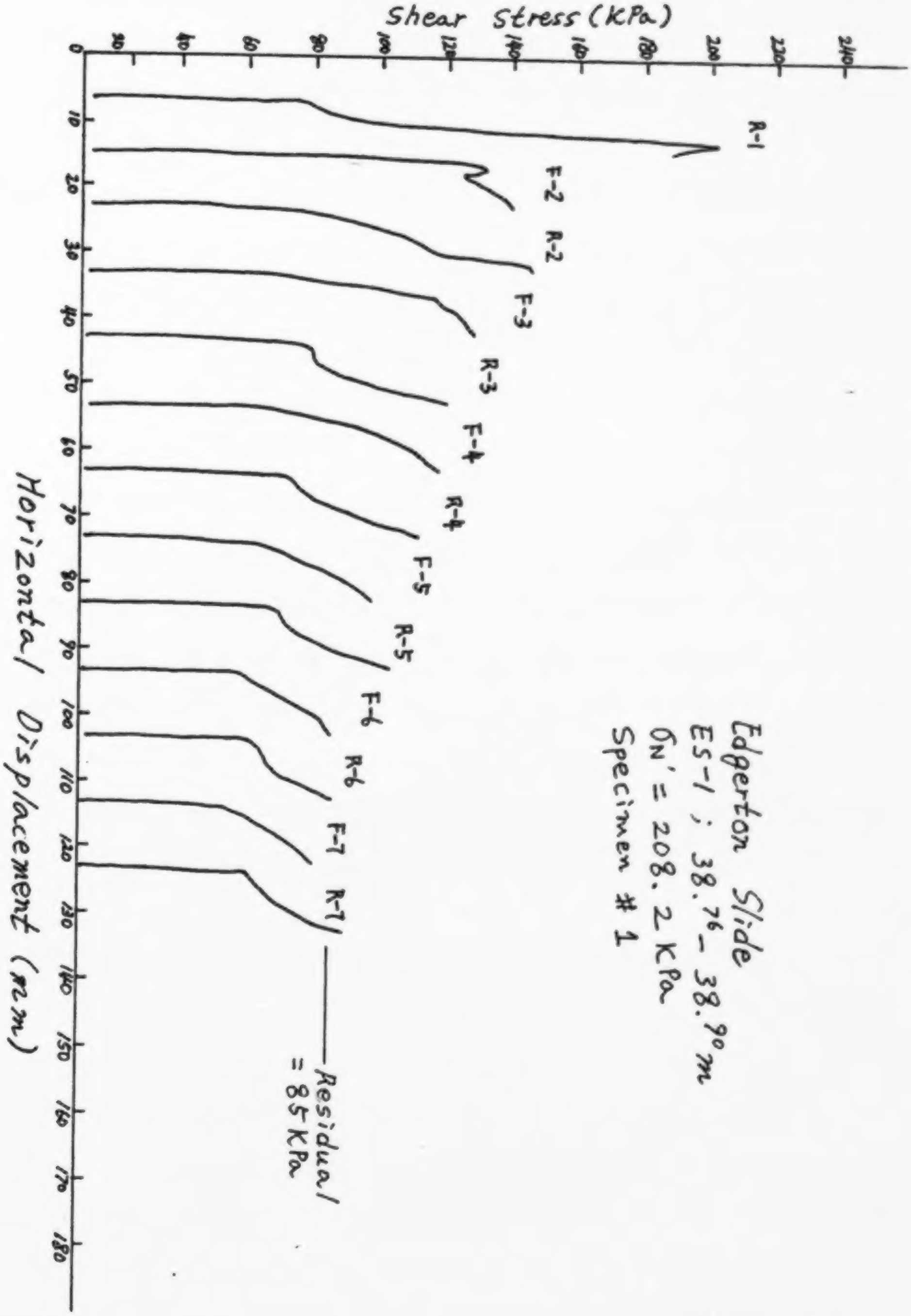
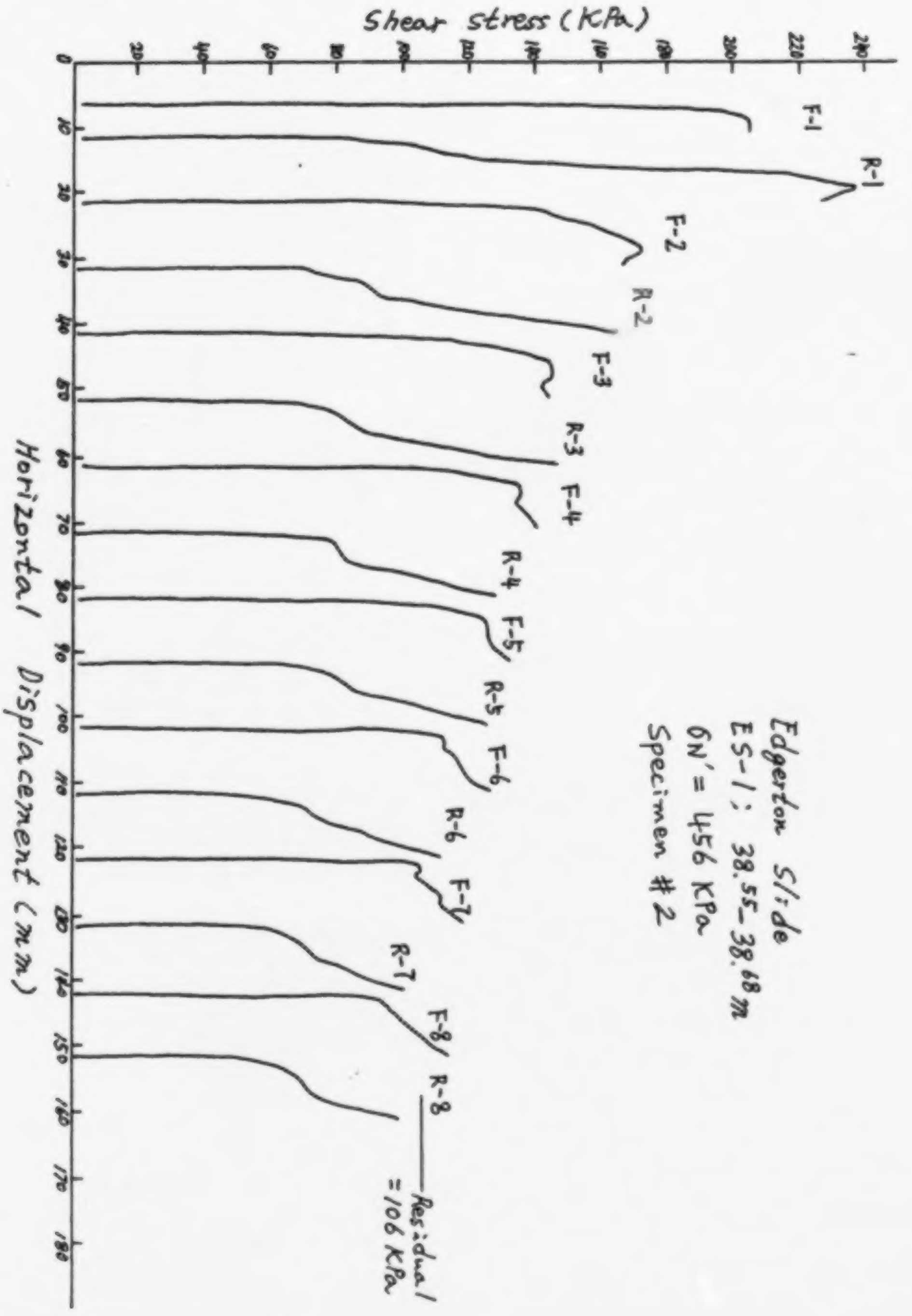
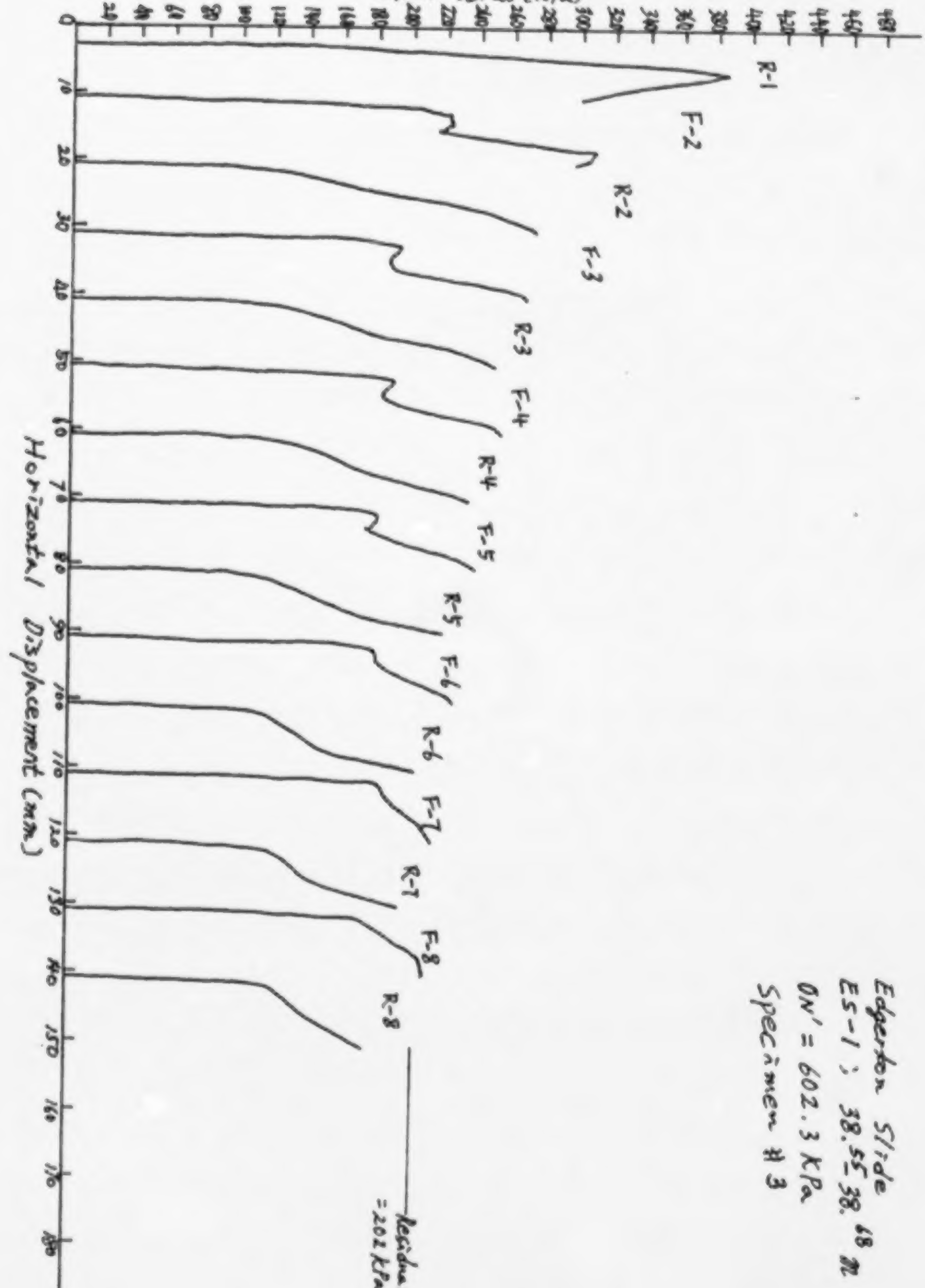


Figure A.2 Load-displacement curve of residual tests

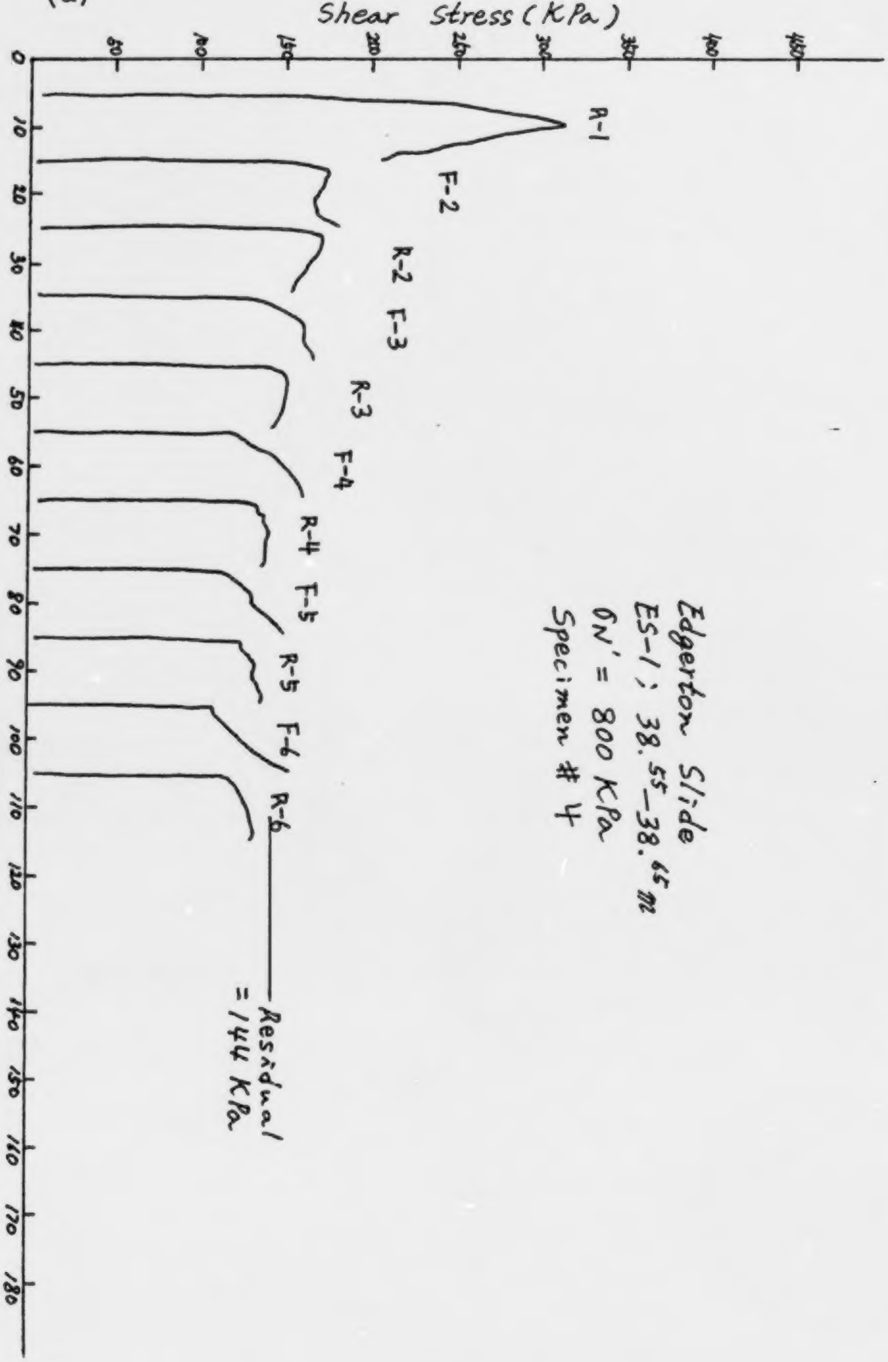
(b)


Shear stress (KPa)
0
20
40
60
80
100
120
140
160
180
200
220
240
Horizontal Displacement (mm)
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
F-1
R-1
F-2
R-2
F-3
R-3
F-4
R-4
F-5
R-5
F-6
R-6
F-7
R-7
F-8
R-8
Residual = 106 KPa
Edgerton Slide
ES-1; 38.55–38.68 m
σN' = 456 KPa
Specimen #2

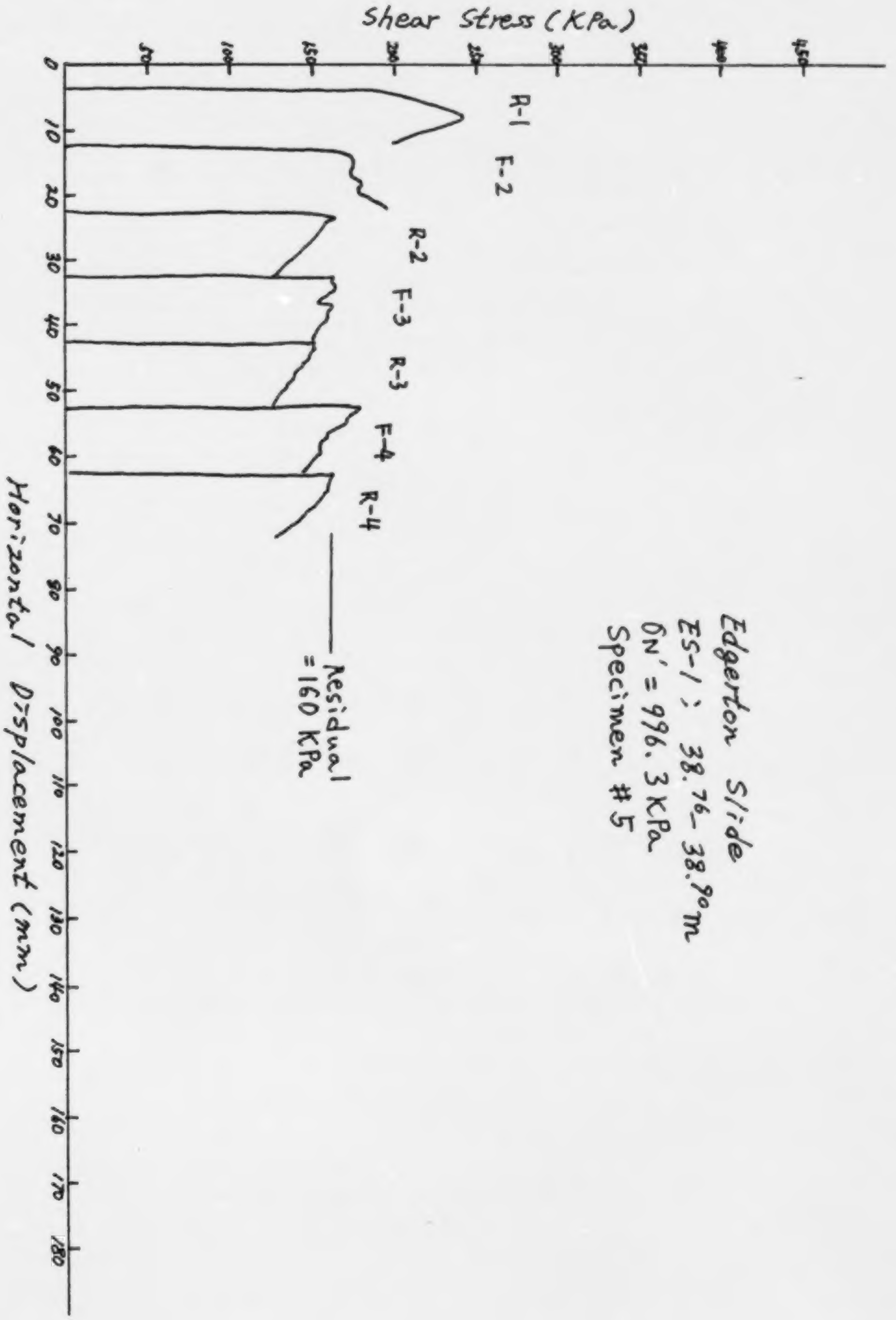
(c)


Shear Stress (KPa)
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
300
320
340
360
380
400
420
440
460
480
Horizontal Displacement (mm.)
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
R-1
F-2
R-2
F-3
R-3
F-4
R-4
F-5
R-5
F-6
R-6
F-7
R-7
F-8
R-8
Residual = 202 KPa
Edgerton Slide
ES-1 ; 38.55–38.68 m
σN' = 602.3 KPa
Specimen # 3

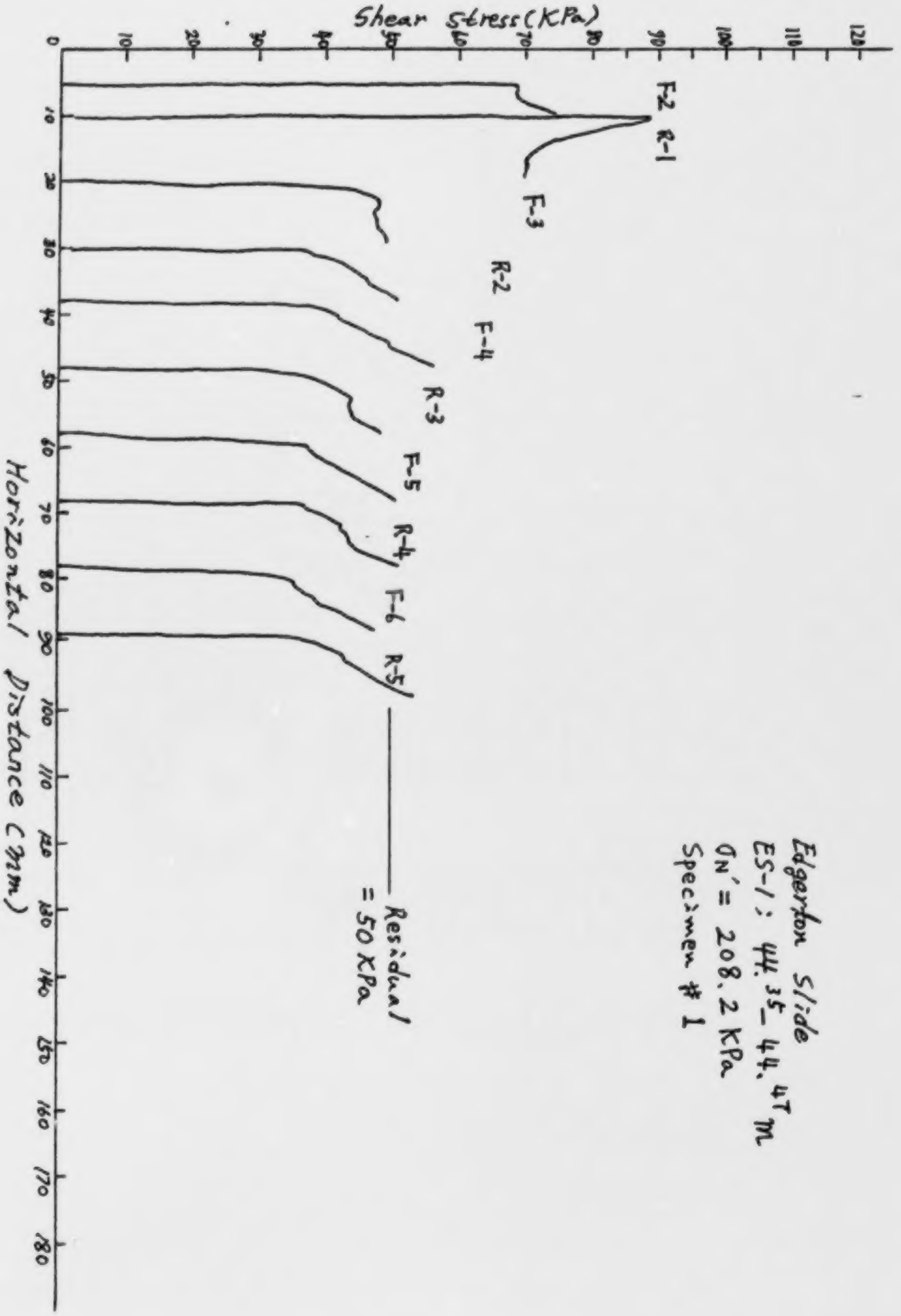
(d)


Shear Stress (KPa)
0
50
100
150
200
250
300
350
400
450
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Horizontal Displacement (mm)
R-1
F-2
R-2
F-3
R-3
F-4
R-4
F-5
R-5
F-6
R-6
Residual
= 144 KPa
Edgerton Slide
ES-1 ; 38.55–38.65 m
σN' = 800 KPa
Specimen # 4

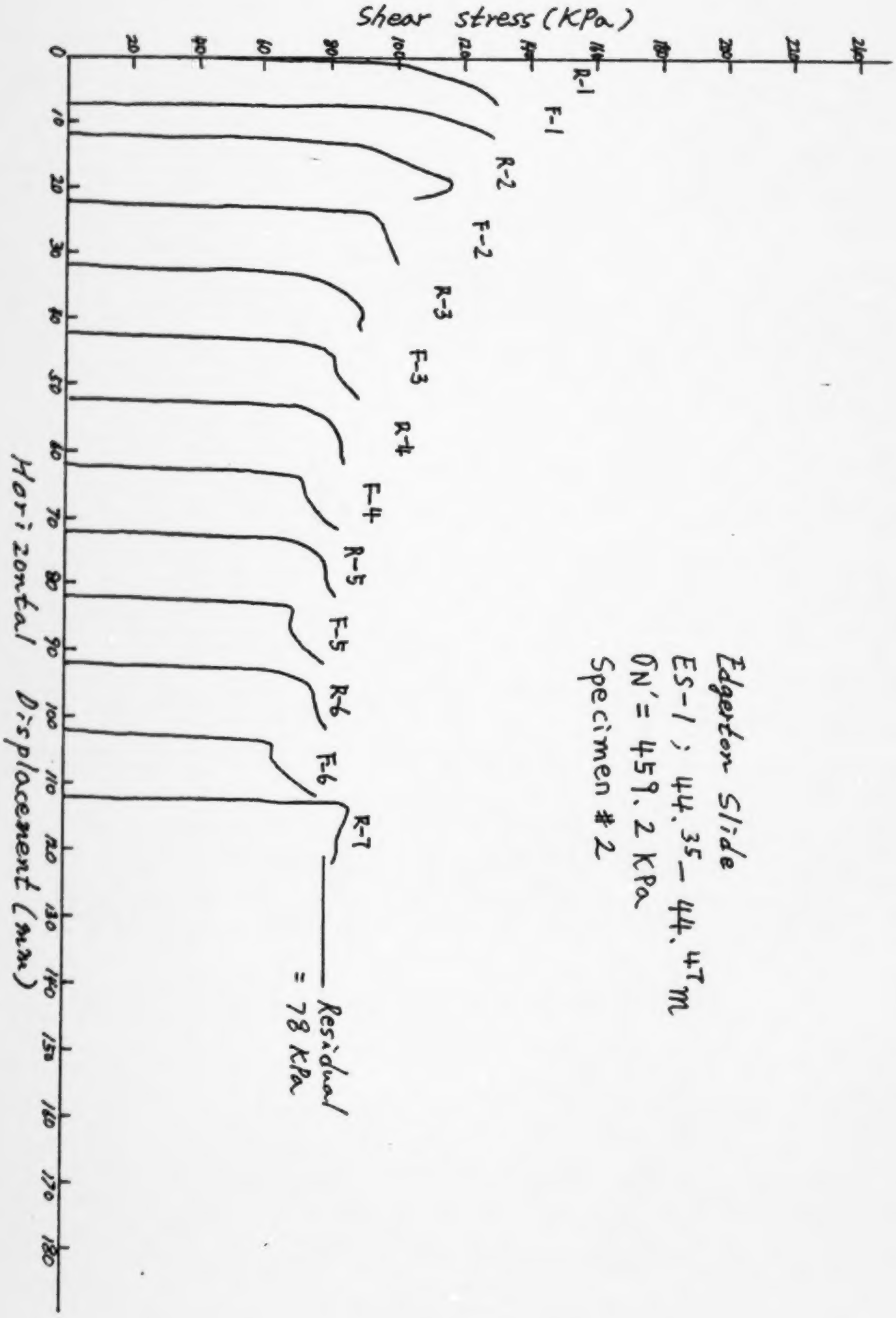
(e)


Shear Stress (KPa)
0
50
100
150
200
250
300
350
400
450
R-1
F-2
R-2
F-3
R-3
F-4
R-4
Residual
=160 KPa
Edgerton Slide
ES-1 ; 38.76 – 38.90 m
σN' = 996.3 KPa
Specimen #5
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Horizontal Displacement (mm)

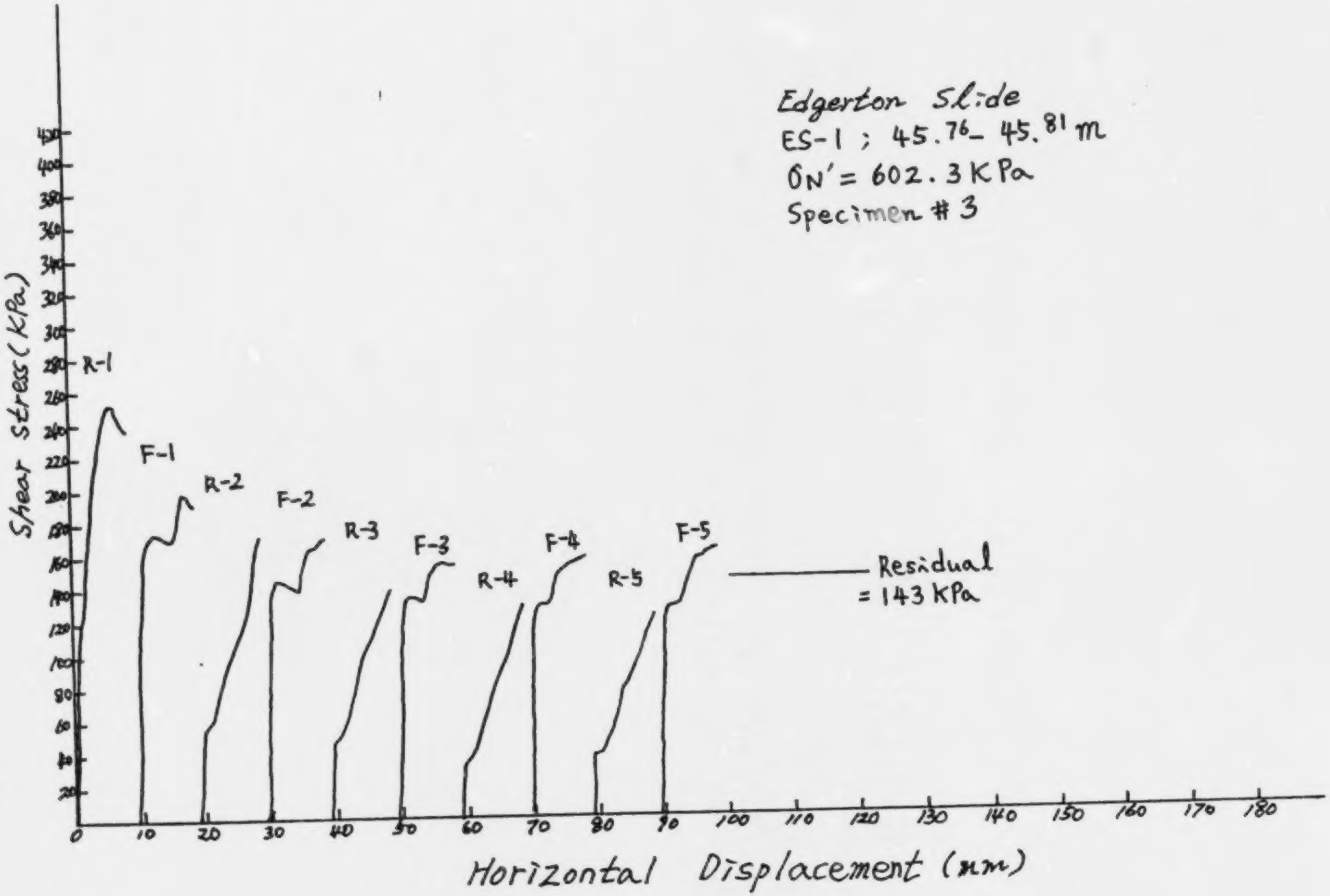
(f)


Shear stress (KPa)
0
10
20
30
40
50
60
70
80
90
100
110
120
Horizontal Distance (mm)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
F-2
R-1
F-3
R-2
F-4
R-3
F-5
R-4
F-6
R-5
Residual = 50 KPa
Edgerton Slide
ES-1 ; 44.35 – 44.47 m
σN' = 208.2 KPa
Specimen # 1

(g)

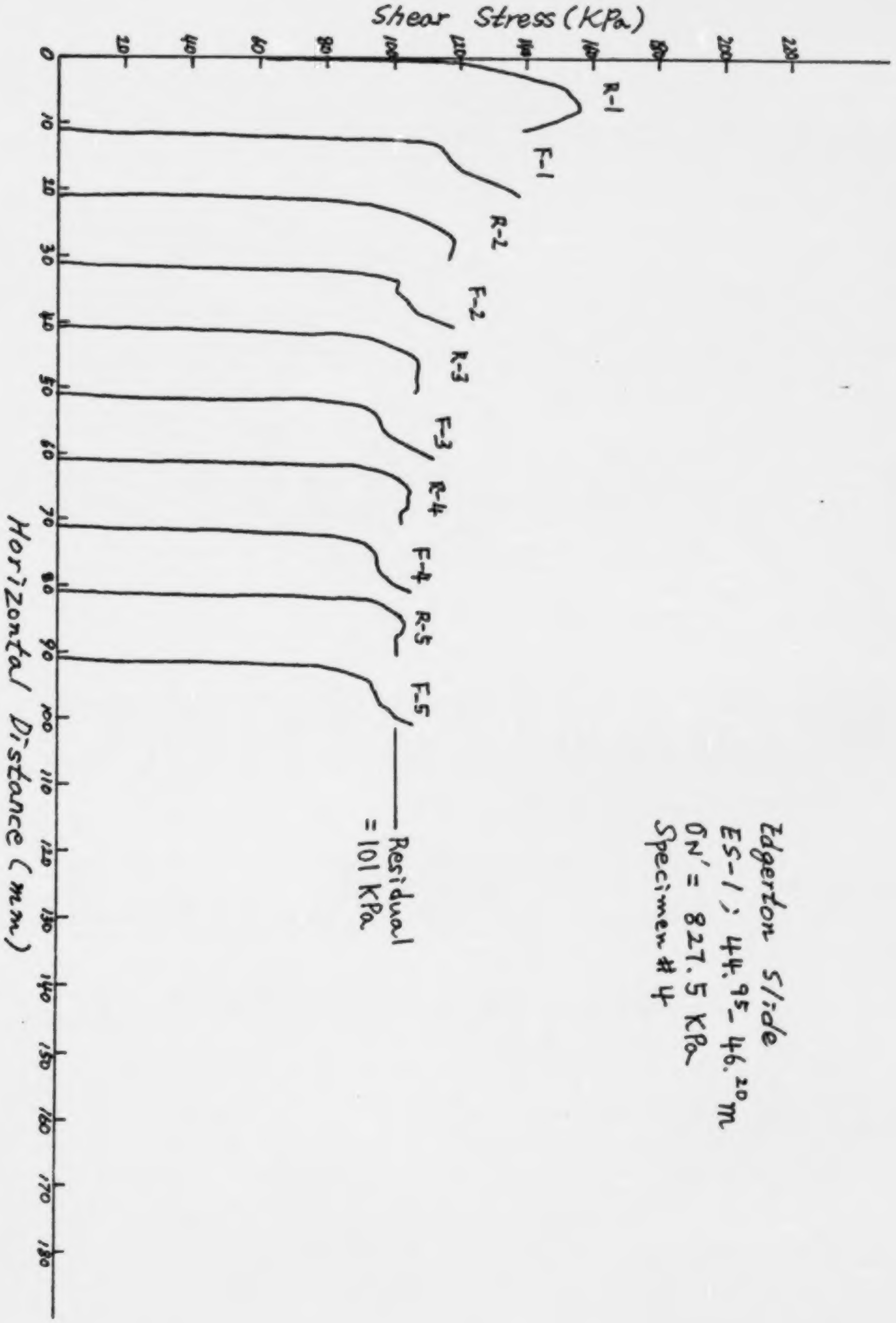

Shear stress (KPa)
0
20
40
60
80
100
120
140
160
180
200
220
240
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Horizontal Displacement (mm)
R-1
F-1
R-2
F-2
R-3
F-3
R-4
F-4
R-5
F-5
R-6
F-6
R-7
Residual = 78 KPa
Edgerton Slide
ES-1 ; 44.35 – 44.47 m
σN' = 459.2 KPa
Specimen # 2

(h)

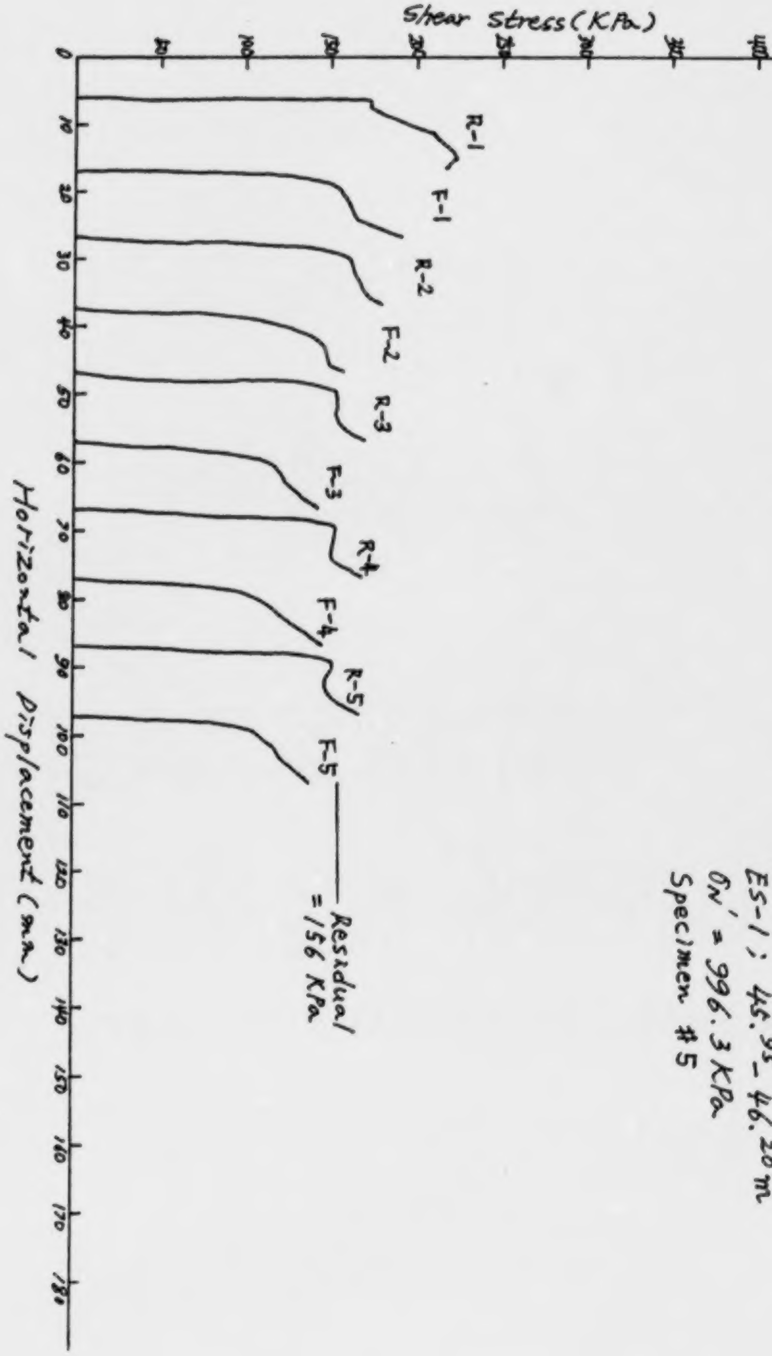


Edgerton Slide
ES-1 ; 45.76 – 45.81 m
$\sigma_N' = 602.3$ KPa
Specimen # 3

(i)


Shear Stress (KPa)
0
20
40
60
80
100
120
140
160
180
200
220
R-1
F-1
R-2
F-2
R-3
F-3
R-4
F-4
R-5
F-5
Residual = 101 KPa
Horizontal Distance (mm)
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Edgerton Slide
ES-1; 44.95-46.20 m
σN' = 827.5 KPa
Specimen #4

(j)


Shear Stress (KPa)
0
50
100
150
200
250
300
350
400
450
Horizontal Displacement (mm)
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
R-1
F-1
R-2
F-2
R-3
F-3
R-4
F-4
R-5
F-5
Residual = 156 KPa
Edgerton Slide
ES-1 ; 45.95 _ 46.20 m
σn' = 996.3 KPa
Specimen #5